PB85-194645

Filtration of 'Giardia' Cysts and Other Substances. Volume 3 Rapid Rate Filtration

Colorado State Univ., Fort Collins

Prepared for

Environmental Protection Agency, Cincinnati, OH

Apr 85

U.S. Department of Commerce
National Technical Information Service
NTIS

PB85-194645

EPA/600/2-85/027
April 1985

FILTRATION OF *GIARDIA* CYSTS AND OTHER SUBSTANCES:
VOLUME 3. RAPID RATE FILTRATION

by

Mohammed Y. Al-Ani
John M. McElroy
Charles P. Hibler
David W. Hendricks

Colorado State University
Fort Collins, Colorado 80523

Cooperative Agreement No. CR808650-02

Project Officer

Gary S. Logsdon
Drinking Water Research Division
Water Engineering Research Laboratory
Cincinnati, Ohio 45268

WATER ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-85/027	2.	3. RECIPIENT'S ACCESSION NO. PB85 194645/AS
4. TITLE AND SUBTITLE Filtration of Giardia Cysts and Other Substances: Volume 3. Rapid Rate Filtration		5. REPORT DATE April 1985 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) M. Al-Ani, J.M. McElroy, C.P. Hibler and D.W. Hendricks		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Colorado State University Department of Civil Engineering Fort Collins, Colorado 80523		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. CR 808650
12. SPONSORING AGENCY NAME AND ADDRESS Water Engineering Research Laboratory-Cincinnati, OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final 3/81 - 2/84 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES Project Officer: Gary S. Logsdon (513) 684-7345

See also: Volume 1, Diatomaceous Earth Filtration, EPA-600/2-84/114
Volume 2, Slow Sand Filtration, EPA-600/2-85/026

16. ABSTRACT

The efficiency of rapid rate filtration for removal of Giardia lamblia cysts, standard plate count bacteria, total coliform bacteria, and turbidity was determined experimentally under a wide range of operating conditions. Percent removal was evaluated by means of a lab-scale pilot plant at temperatures of 4°C and 18°C, for low turbidity water, at hydraulic loading rates of 8 cm/min (2 gpm/ft^2), 24 cm/min (5 gpm/ft^2) and 33 cm/min (8 gpm/ft^2), for "in-line" filtration, for three filter media, and using three chemicals. Testing was performed also using a 1.3 L/s (20 gpm) field-scale rapid rate filtration pilot plant. The range of testing was narrower and focused on ascertaining the findings at the lab-scale.

The results showed that rapid rate filration will effectively treat low turbidity water, and will remove Giardia cysts if proper chemical pretreatment is used. Proper chemical pretreatment is difficult to determine and to evaluate for low turbidity waters since the usual measures of effectiveness such as turbidity removals and coliform bacteria removals are based upon very low amounts in the raw water. Pilot plant testing is imperative to ascertain proper chemical pretreatment, when using low turbidity waters.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 302
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement number CR808650-02 to Colorado State University. It has been subject to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

Giardiasis is an intestinal disease reported with increasing frequency, especially in the western and northeastern United States. The disease is caused by ingestion of cysts of the protozoan _Giardia lamblia_. The cysts are commonly found in the cold, clear streams of mountain environments, which are used as a source water supply by many communities. This report investigates the effectiveness of rapid-rate filtration in removal of _Giardia_ cysts and other substances of concern; it delineates the role of selected design criteria and operating conditions. The problems associated with rapid rate filtration are examined as a part of the EPA research program focused on the water treatment problems of small communities. Special reference is made to the difficulties with cold, low turbidity raw waters.

Francis T. Mayo
Director, Water Engineering Laboratory

ABSTRACT

FILTRATION OF GIARDIA CYSTS AND OTHER SUBSTANCES
VOLUME 3: RAPID RATE FILTRATION

The efficiency of rapid rate filtration for removal of *Giardia lamblia* cysts, standard plate count bacteria, total coliform bacteria, and turbidity was determined experimentally under a wide range of operating conditions. Percent removals were evaluated by means of a lab-scale pilot plant at temperatures of 4°C and 18°C, for low turbidity water, at hydraulic loading rates of 8 cm/min (2 gpm/ft²), 24 cm/min (5 gpm/ft²) and 33 cm/min (8 gpm/ft²), for "in-line" filtration, for three filter media, and using three chemicals. Testing was performed also using a 1.3 L/s (20 gpm) field-scale rapid rate filtration pilot plant. The range of testing was narrower and focused on ascertaining the findings at the lab-scale.

The study has shown that rapid rate filtration is a highly efficient treatment process for low turbidity waters when proper chemical pretreatment is used. Certain polymers, such as Magnifloc 572C® or Magnifloc 573C® in conjunction with alum will effectively coagulate low turbidity, low temperature water, i.e. when raw water turbidity level is less than 1 NTU, and when temperature is 0-4°C. Lab-scale results, for example, showed that using 5 mg/L of alum as $Al_2(SO_4)_3.14H_2O$ followed by 1.5 mg/L Magnifloc 572C, *Giardia* cyst removals were 99 percent, and standard plate count bacteria and total coliform bacteria removals were greater than 99 percent. At the same time, corresponding turbidity removals of about 80 percent were obtained using raw water having less than 1 NTU turbidity. With no chemical pretreatment, removals of all substances, including *Giardia* cysts, ranged from only 10 percent to 70 percent.

The results showed that rapid rate filtration will effectively treat low turbidity water, and will removal *Giardia* cysts if proper chemical pretreatment is used. Proper chemical pretreatment is difficult to determine and to evaluate for low turbidity waters since the usual measures of effectiveness such as turbidity removals and coliform bacteria removals are based upon very low amounts in the raw water. Pilot plant testing is imperative to ascertain proper chemical pretreatment, when using low turbidity waters.

This report was submitted by Colorado State University to fulfill Cooperative Agreement No. CR808650-02, funded by the U.S. Environmental Protection Agency. It covers the period March 1, 1981 to February 28, 1984, and work was completed as of February 28, 1984.

CONTENTS

Foreword.......... iii
Abstract.......... iv
Tables.......... ix
Figures.......... xiii
Acknowledgments.......... xxiii

1. Introduction.......... 1
  Context of Research.......... 1
  Investigation.......... 2
    Purpose.......... 2
    Objectives.......... 2
    Scope.......... 2
    Significance.......... 3
  Giardiasis.......... 4
  Treatment of Mountain Waters.......... 6
    Characteristics.......... 6
    Treatment Practices.......... 8
    Problems in Treatment.......... 8
  Literature Review on Rapid Rate Filtration.......... 9
    Development.......... 9
    Principles.......... 11
    Modern Theory.......... 12
    Filtration of Low Turbidity Waters.......... 13
    Effect of Temperature.......... 13
    Filtration of Giardia Cysts.......... 14

2. Summary and Conclusions.......... 15
  Chemical Pretreatment.......... 15
  Removals.......... 16
  Process Variables.......... 16
    Coagulant Selection.......... 16
    Dosages of Coagulants.......... 17
    Field-Scale Testing of Coagulants.......... 17
      Filtration Without Cogaulation.......... 17
      Coagulation of Horsetooth Reservoir Water.......... 17
      Coagulation of Cache La Poudre River Water.......... 17
    Sequence of Coagulant Additions.......... 18
    Mode of Filtration.......... 18
    Comparison of Media.......... 18
    Filtration Rate.......... 19
    Temperature.......... 19

Run Time... 19
Surrogate Indicators of Giardia Removal.................... 19

3. Methods.. 21
Research Plan.. 21
Testing Space.. 21
Experimental Design.. 23
Plan of Experimentation - Laboratory-Scale Pilot Plant... 23
Plan of Experimentation - Field-Scale Pilot Plant..... 26
Pilot Plant - Laboratory-Scale............................. 27
Description of Laboratory-Scale Pilot Plant........... 27
Water Storage.. 27
Pump... 30
Rapid Mix.. 30
Chemical Storage... 31
Flocculation Basins.. 31
Sedimentation Basins....................................... 33
Filters.. 34
Operation.. 34
Sources of Water... 34
Flow... 34
Rapid Mix.. 39
Chemical Feed.. 40
Flocculation... 40
Sedimentation.. 40
Filtration... 40
Screening Chemicals.. 42
Pilot Plant - Field-Scale.................................. 42
Description of Field-Scale Pilot Plant................ 42
Appurtenances Utilized with Pilot Plant............... 43
Test Conditions for Field-Scale Pilot Plant........... 45
Raw Water.. 45
Filtration Conditions...................................... 45
Coagulants... 45
Measurements and Quality Control........................... 46
Procurement of Giardia Cysts............................... 46
Laboratory-Scale Measurements and Quality Control..... 46
Cyst Sampling.. 49
Counting... 49
Field-Scale Measurements and Quality Control.......... 49
Flow Measurements.. 49
Temperature.. 49
Turbidity.. 50
Bacteria... 50
Bacterial Analyses... 50
Headloss Measurement....................................... 52
Injection of Giardia Cysts................................. 52
Giardia Sampling... 52
Giardia Measurement Quality Control........................ 55

Data Handling.. 55
Aquisition of Data.................................. 55
Data Processing..................................... 58
Master Data Table................................... 58
Plots, Tables, and Statistical Analyses............. 58

4. Results and Discussion................................. 59
Removals - Laboratory-Scale Pilot Plant................ 59
Turbidity... 61
Standard Plate Count Bacteria....................... 61
Total Coliform Bacteria............................. 61
Particles... 61
Giardia Cyst.. 61
Effect of Process Variables............................ 62
Coagulant Selection................................. 63
Dosages of Coagulants............................... 64
Sequence of Coagulant Addition...................... 71
Mode of Filtration.................................. 71
Comparison of Single and Dual Media................. 75
Filtration Rate..................................... 75
Temperature... 75
Run Time.. 81
Relationships Between Dependent Variables.............. 84
Surrogate Indicators of _Giardia_ Cyst Removal...................................... 86
Turbidity... 86
Total Coliform Bacteria............................. 89
Standard Plate Count Bacteria....................... 89
Particles... 89
Turbidity Removal As A Surrogate.................... 89
Field-Scale Pilot Plant Testing........................ 92
Coagulant Dosage Determination...................... 94
Effect of Coagulant Dose on Filtration.............. 94
Zero Coagulant Dose Tests........................ 100
Optimum Coagulant Dose Tests..................... 100
Nonoptimum Coagulant Dose Tests.................. 100
Associations Between Dependent Variables............ 100
Horsetooth Water..................................... 101
Summary of Results for Field-Scale Pilot Plant Testing 102

REFERENCES.. 103

APPENDICES
A - MASTER DATA TABLE FOR LABORATORY-SCALE RAPID RATE FILTRATION PILOT PLANT.................................. 111

B - MASTER DATA TABLE FOR FIELD-SCALE RAPID RATE FILTRATION PILOT PLANT.................................. 128

C - DESIGN OF LABORATORY-SCALE RAPID RATE FILTRATION PILOT PLANT... 138

D - DESCRIPTION OF THE FIELD-SCALE RAPID RATE FILTRATION PILOT PLANT AND ITS OPERATION............... 154

E - DATA COLLECTION FORMS................................ 170

F - STATISTICAL ANALYSIS OF DATA........................... 178

G - SUPPORTING GRAPHS...................................... 183

H - RESULTS FROM FAMILIARIZATION TESTING, HORSETOOTH HORSETOOTH TESTING AND SPRING RUNOFF TESTING........... 205

I - CHEMICALS... 229

J - GIARDIA PROCUREMENT, ANALYSIS AND DETECTION LIMITS..... 249

TABLES

Table Page

1 Characteristics of Cache La Poudre River water for calendar year 1979 at Fort Collins Water Treatment Plant No. 1....... 7

2 Characteristics of water from Horsetooth Reservoir during 1979 at Fort Collins Water Treatment Plant No. 1 during months of operation.......................... 7

3 Process variables and their operating conditions during rapid rate filtration experiments for Giardia cyst removal.. 25

4 Dependent variables measured in testing rapid rate filtration performance.................................. 26

5 Appurtenances for field-scale rapid rate filtration pilot plant.. 44

6 Raw water characteristics for field-scale testing (average yearly ranges).................................. 45

7 Filtration conditions for field-scale pilot plant testing... 45

8 Sampling and measurement of filtration efficiency parameters obtained in operation of laboratory-scale rapid rate filtration pilot plant.......................... 47

9 Monitoring measurements and quality control in operation of laboratory-scale rapid rate filtration pilot plant....... 48

10 Effect of chemical pretreatment on removal of turbidity, standard plate count bacteria, total coliform bacteria, particles and Giardia cysts for low turbidity artificial water, and low turbidity Cache La Poudre River water, by "in-line" rapid sand filtration........................ 60

11 Removals of turbidity, standard plate count bacteria, total coliform bacteria, and Giardia cysts, for different conditions of chemical pretreatment. Data shown are for low turbidity raw water, e.g. less than 1.5 NTU and for all conditions of hydraulic loading rate, media temperature, and source of water...................................... 65

Table Page

12 Filter effluent turbidity for low turbidity low temperature water with pretreatment using alum and Magnifloc 572C polymer. Data were obtained using sources indicated........ 70

13 "In-line" filtration versus direct filtration data........ 73

14 Comparison of effluent and headloss for single and dual media using laboratory-scale rapid rate filtration pilot plant........ 76

15 Effect of filtration rate on removals of turbidity, standard plate count bacteria, total coliform bacteria, and _Giardia_ cysts for dual media using two sources of sand. All other conditions were approximately the same. Laboratory-scale rapid rate filtration pilot plant were used. Coagulant dosages were those in which minimum effluent turbidity was attained........ 77

16 Effect of temperature on removal of turbidity, standard plate count bacteria, total coliform bacteria, for different chemical dosages........ 80

17 Effect of elapsed time after backwash on removal of _Giardia_ cysts, particles, standard plate count bacteria, total coliform bacteria, for low turbidity, low temperature water at "optimum" and "non-optimum" coagulant dosages........ 85

18 Results of twenty three effluent turbidity vs chemical dose tests using low-turbidity raw water. Data points for chemical dose and corresponding effluent turbidity were used to construct Figures 4-16 through 4-20........ 95

19 _Giardia_ and coliform results from testing using low-turbidity raw water........ 99

A-1 Master data table for laboratory-scale rapid rate filtration pilot plant........ 112

A-2 _Giardia_ cyst removal efficiency corrected for detection limit........ 124

B-1 Master Data Table........ 129

D-1 Appurtenances for operation of field-scale rapid rate filtration pilot plant........ 158

Table		Page
E-1	Example of feed tank data obtained during test run using laboratory-scale rapid rate filtration pilot plant	171
E-2	Example of data collection during test run for laboratory-scale rapid rate filtration pilot plant	172
E-3	Standard plate count bacteria data obtained during analysis of samples taken during operation of laboratory-scale rapid rate filtration pilot plant	173
E-4	Total coliform bacteria data obtained during analysis of samples taken during operation of laboratory-scale rapid rate filtration pilot plant	174
E-5	Particle count data obtained during analysis of samples taken during operation of laboratory-scale rapid rate filtration pilot plant	175
E-6	Giardia cyst data obtained during analysis of samples taken during operation of laboratory-scale rapid rate filtration pilot plant	176
E-7	Sample data sheet for field-scale pilot plant	177
F-1	Showing an example of calculating an estimated probability	181
H-1	Effect of coagulant dosages on removals of coliform bacteria and Giardia cysts for Horsetooth water	212
H-2	Spring runoff results	219
J-1	Cyst concentration by membrane filter sampling compared cyst concentration in source tank as determined by grab sample. Analysis by micropipette technique for both sampling methods. Tests conducted in laboratory of Dr. Charles Hibler, July 1982	256
J-2	Comparison of cyst recovered by sampling milk cooler feed tank water using membrane filters with cyst concentrations in tank as computed after adding cyst concentrate suspension. Analyses performed during slow sand filter experiments	257
J-3	Giardia cysts counted by three individuals using the micropipette technique at 1:1 dilution	268

Table		Page
J-4	*Giardia* cysts counted by three individuals using the micropipette technique at 1:5 dilution	268
J-5	*Giardia* cysts counted by three individuals using the Stoll technique	270
J-6	*Giardia* cysts recovered after passage through the push-pull pump and the filter	272
J-7	*Giardia* cysts/ml determined to be present in the tank prior to trial. Direct micropipette counts, 1:1 dilution of 1 cc samples	274
J-8	*Giardia* cysts/ml obtained following the push-pull pump and filtering through the nucleopore filter. All counts performed by direct micropipette, 1:5 dilution	275
J-9	*Giardia* cysts/ml obtained using the vacuum pump to pull sample through the nucleopore filter. All counts performed by direct micropipette, 1:5 dilution	276

FIGURES

Figure		Page
1	Sketches of a) trophozoite and b) cyst stages of *Giardia lamblia* (Jackubowski and Hoff, 1979)	6
2	Experimental testing space illustrating the range of experimental work	22
3	Matrix of testing space illustrating conceptually a possible sequence of experiments using the laboratory-scale rapid rate filtration pilot plant	24
4	Schematic drawing of laboratory-scale rapid rate filtration pilot plant	28
5	Photograph of laboratory-scale rate filtration pilot plant	29
6	Milk cooler for storage and temperature control of raw water supply for laboratory-scale rapid rate filtration pilot plant	30
7	Rapid mix units, laboratory-scale rapid rater filtration pilot plant	31
8	Chemical feed tanks and metering pumps, laboratory-scale rapid rate filtration pilot plant	32
9	Flocculation basins with paddles, motor, and rheostats for laboratory-scale rapid rate filtration pilot plant	32
10	Sedimentation tank, for laboratory-scale rapid rate filtration pilot plant	33
11	Sieve analysis for filter sand, used in sand filter and sand portion of dual media filter laboratory-scale rapid rate filtration pilot plant. Source of sand is Loveland treatment plant at Big Thompson Canyon	35
12	Sieve analysis for anthracite used in dual media filter, laboratory-scale rapid rate filtration pilot plant. Anthracite has brand name Philterkal Special No. 1	36

Figure		Page
13	Close-up of 10 cm diameter filter column, laboratory-scale rapid rate filtration pilot plant..........................	37
14	Membrane filter, 142 mm diameter, set up for Giardia cyst sampling of filter effluent, laboratory-scale rapid rate filtration pilot plant..................................	38
15	Tanks mounted on trailer for hauling water from Cache La Poudre River for laboratory-scale rapid rate filtration pilot plant. Tank capacity is 1000 liters each cylinder. Lining is stainless steel..................................	39
16	Schematic diagram of the WATER BOY pilot plant showing chemical feed, contaminant feed, and sampling system........	41
17	WATER BOY pilot plant on 22 foot trailer. The large cylindrical tank is the 4000 l clear well..................	43
18	Hach ratio turbidimeter model 18900-10 used to measure turbidity..	51
19	a) Hach flow-through turbidimeters, b) flow meter used to measure main flow, c) backwash valve #1, d) effluent flow control valve...	51
20	Side view of WATER BOY: a) headloss board with piezometers, b) main control panel, c) backwash hose, d) minor control panel..	53
21	Contaminant feed system: a) batch tank, b) mixer, c) injection port, d) metering pump, e) four elbows for mixing contaminants with raw water, f) raw water line, g) influent sampling port for Giardia, coliforms, and turbidity...	53
22	a) Membrane filter holder used to hold 5 m pore size, 293 mm diameter membrane filters..........................	54
23	a) Giardia sampling pump, b) effluent sampling port for Giardia, c) dampener to stabilize the sampling stream, d) flow meter used to measure sampling flow rate...........	54
24	Membrane filter holder being opened allowing excess water to flow into pyrex tray..................................	56
25	Top of membrane filter holder being rinsed, allowing wash water to flow into pyrex tray.............................	56

Figure Page

26 Membrane filter being rinsed. The cysts which were strained from the sampling stream are transferred to the pyrex tray.......... 57

27 Transferring the contents of the pyrex tray to the mason jar.......... 57

28 Comparison of turbidity reduction in jar-filtration testing by five polymers (Choi, 1983).......... 63

29 Histogram of turbidity percent removal and coagulant tested, using laboratory-scale rapid rate pilot plant. Each block represents one measurement set.......... 66

30 Histogram of *Giardia* cysts percent removal and coagulant tested, for laboratory-scale rapid rate pilot plant. Each block represents one measurement set.......... 67

31 Turbidity of filtered water for various combinations of alum and polymer (Magnifloc 572C). Shaded bars were obtained using laboratory-scale rapid rate pilot plant. Open bars were obtained using jar-filtration apparatus. All tests were conducted at 3-5°C. Raw water turbidities were less than 1 NTU with exceptions as noted in Table 4-3).......... 69

32 Histogram of *Giardia* cysts percent removal and dosage of Magnifloc 572C as coagulant aid using laboratory scale rapid rate pilot plant. Each block represents one measurement set.......... 72

33 Comparison of turbidity and headloss, for "in-line" and "direct" filtration. Laboratory-scale pilot plant using artificial low turbidity water from Horsetooth Reservoir, and dual media Fort Collins sand.......... 74

34 Effect of hydraulic loading rate on percent removals of turbidity, standard plate count bacteria, total coliform bacteria, and *Giardia* cysts, using laboratory-scale, rapid rate filtration pilot plant packed with dual media with Fort Collins sand.......... 78

35 Effect of hydraulic loading rate on percent removals of turbidity, standard plate count bacteria, total coliform bacteria, and *Giardia* cysts using laboratory-scale rapid rate filtration pilot plant packed with dual media with Loveland sand.......... 79

Figure Page

36 Effect of run time on turbidity reduction for different temperatures and coagulants. Figures H-7 to H-11, Appendix H describe complete conditions.................... 82

37 Effect of run time on headloss for different temperatures and coagulants. Figures H-7 to H-11, Appendix H describe complete conditions.............................. 83

38 Histogram showing percent removal of Giardia cysts with corresponding percent removal of turbidity. Each block represents one measurement set. Data points are for water having turbidity of less than 1 NTU, and temperatures 3-5°C... 87

39 Probability of a given percent removal of Giardia cysts for specified percent removals of turbidity. Data obtained from Table A-1 and Table A-2 plotted in Figure H-12.. 88

40 Histogram showing percent removal of Giardia cysts with corresponding percent removal of total coliform bacteria. Each block represents one measurement set........ 90

41 Probability of a given percent removal of Giardia cysts for specific percent removal of total coliform bacteria. Data from Table A-1 and Table A-2 plotted in Figure H-13.. 91

42 Histogram showing percent removal of total coliform removal with corresponding percent removal of turbidity. Each block represents one measurement set. Data points are for all water tested........................ 93

43 Effluent turbidity vs Nalco 8102 dose. Low-turbidity water.. 96

44 Effluent turbidity vs Nalco 8102 dose using 3 mg/l of alum, $Al_2(SO_4)_3 \cdot 14H_2O$, for low-turbidity water.. 97

45 Effluent turbidity vs alum dose, $Al_2(SO_4)_3 \cdot 14H_2O$, for low-turbidity water..................................... 97

46 Effluent turbidity vs dose of Magnifloc 572-C. Low-turbidity water... 98

47 Effluent turbidity vs alum dose, $Al_2(SO_4)_3 \cdot 14H_2O$, using 2 mg/l of Magnifloc 572-C for low-turbidity water..... 98

Figure Page

48 Percent removal of *Giardia* cysts vs percent removal of coliform bacteria for low-turbidity water. Raw water characteristics were: <1°C and <1 NTU........................ 101

C-1 Schematic drawing of laboratory-scale rapid rate filtration pilot plant.................................. 139

C-2 Measurements of a turbine mixer in a baffle tank (Hendricks, 1976).................................... 140

C-3 Detailed design of rapid mix basin........................ 142

C-4 Detailed design of flocculation basin...................... 146

C-5 Detailed design of sedimentation basin.................... 148

C-6 Filter design detail...................................... 150

C-7 Velocity gradient (G sec^{-1}) versus revolution per minute of paddle shaft for coagulation box. Laboratory scale rapid rate filtration pilot plant. Volume of box is 2048 cm^3. Paddle design shown in Figure C-3......... 152

C-8 Velocity gradient (G sec^{-1}) versus revolution per minute (rpm) for flocculation compartment. Laboratory scale rapid rate filtration pilot plant. Volume of compartment is 8390 cm^3.................................. 153

D-1 The Neptune Microfloc WATER BOY® field-scale rapid rate filtration pilot plant as set up at the Fort Collins Water Treatment Plant No. 1 for low-turbidity testing. Water was obtained from the Cache La Poudre River........... 154

D-2 Neptune Microfloc diagram of the WATER BOY® showing elevation ad plan views..................................... 155

D-3 Neptune Microflow flow diagram of the WATER BOY® showing processes and hydraulics.......................... 156

D-4 Filration media used during familiarization testing. Media used was packed by Clarkson College of Technology, Postdam, New York... 157

D-5 Filtration media used during Spring Runoff, Horsetooth, and Low-Turbidity testing. Anthracite was obtained from the Fort Collins Water Treatment Plant No. 1, and the sand was obtained from the Fort Collins Treatment Plant No. 2.. 157

Figure Page

D-6 Schematic diagram of the WATER BOY pilot plant showing chemical feed, contaminant feed, and sampling systems....... 159

D-7 Side view of WATER BOY: a) major control panel, b) minor control panel, c) effluent-flow pump, d) garden-hose-valve.. 161

D-8 Raw water pump (1 /2 hp).. 161

D-9 Top view of rapid mix basin: a) influent-flow-control valve, b) mixer, c) raid mix basin.......................... 162

D-10 Effluent flow control: a) effluent-flow-control valve, b) effluent-flow-pump-protector switch, c) shaft connected to effluent-flow-control-float, d) butterfly nut............ 163

D-11 Chemical feed system: a) polymer tak, b) alum tank, c) alum pmp, d) polymer pump, e) electrical boxes, f) speed controller for polymer mixer, g) polymer injection port, h) alum injection port, i) influent raw water.. 165

D-12 Contaminant feed system: a) batch tak, b) mixer, c) injection port, d) metering pump, e) four elbows for mixing contaminants with raw water, f) raw water influent line, g) influent sampling port for *Giardia*, coliforms, and turbidity.. 165

D-13 Portion of apparatus for sampling *Giardia* cysts in effluent stream: a) *Giardia* sampling pump, b) effluent sampling port for *Giardia*, c) dampener to attenuate pressure fluctuations in the sampling stream, d) flow meter used to measure sampling flow rate.................... 168

F-1 Observations of percent removal of *Giardia* cysts with corresponding percent removal of turbidity. Data obtained from Table A-1 and Table A-2. The solid points show the median for each 8 points, connected by line........ 179

F-2 Probability of a given percent removal of *Giardia* cysts for specified percent removals of turbidity. Data obtained from Table A-1 and Table A-2 plotted in Figure E-12.. 182

G-1 Effect of sequence of alum-polymer additions on effluent turbidity, laboratory-scale pilot plant using dual media with Fort Collins sand, artificial low turbidity wate from Horsetooth Reservoir, and "in-line" filtration... 184

Figure | Page

G-2 Effect of sequence of alum-polymer additions on effluent turbidity, laboratory-scale pilot plant using dual media with Fort Collins sand, artificial low turbidity water from Horsetooth Reservoir and "in-line" filtration.......... 185

G-3 Comparison of turbidity and headloss for "in-line" and "direct" filtration laboratory-scale pilot plant using dual media Fort Collins sand, artificial low turbidity water from Horsetooth Reservoir.......... 186

G-4 Comparison of turbidity and headloss for single and dual media of Loveland sand, with no cheical pretreatment. Laboratory-scale using artificial low turbidity water from Horsetooth Reservoir, and "in-line" filtration.......... 187

G-5 Comparison of turbidity and headloss for single and dual media of Loveland sand, with optimum chemical pretreatment. Laboratory-scale pilot plant, using artificial low turbidity water from Horsetooth Reservoir and "in-line" filtration.......... 188

G-6 Comparison of turbidity and headloss for single and dual media of Loveland sand, with alum pretreatment. Laboratory-scale pilot plant using artificial low turbidity water from Horsetooth Reservoir and "in-line" filtration.......... 189

G-7 Effluent turbidity and headloss versus time, showing the effect of temperature on turbidity reduction, and headloss.......... 190

G-8 Effluent turbidity and headloss versus time, showing the effect of temperature on turbidity reduction and headloss for adding alum and Magnifloc 572C in the same basin.......... 191

G-9 Effluent turbidity and headloss versus time, showing the effect of temperature on turbidity reduction and headloss when alum was added and then Magnifloc 572C in two coagulant basins.......... 192

G-10 Effluent turbidity and headloss versus time, showing the effect of temperature on turbidity reduction and headloss when Magnifloc 572C was added before alum in two coagulant basins.......... 193

Figure Page

G-11 Effluent turbidity versus time, showin the effect on turbidity reduction and headloss of using alum alone or Magnifloc 572C alone.................................. 194

G-12 Observations of percent removal of _Giardia_ cysts with corresponding percent removal of turbidity. Data obtained from Table A-1 and Table A-2. The solid points show the median for each 8 points, connected by line........ 195

G-13 Observations of percent removal of _Giardia_ cysts with corresponding pecent removal of total coliform bacteria. Data obtained from Table A-1 and Table A-2. The solid points show the median for each 9 points, connected by a line.. 196

G-14 Observation of percent removal of _Giardia_ cyst with corresponding percent removal of standard plate count bacteria. Data obtained from Table A-1 and Table A-2. The solid points show the median for each 8 points connected by a line.. 197

G-15 Probability of a given percent removal of _Giardia_ cysts for specific percent removal of standard plate count bacteria. Data from Table A-1 and plotted in Figure G-14... 198

G-16 Observation of percent removal of total coliform from bacteria with corresponding percent removal of turbidity. Data obtained from Table A-1. The solid points show the median for each 10 points connected by a line.. 199

G-17 Probability of a given percent removal of total coliform bacteria for specific percent removal of turbidity. Data from Table A-1 and plotted in Figure G-13... 200

G-18 Observations of percent removal of standard plate count with corresponding percent removal of turbidity. Data obtained from Table A-1. The solid points show the median for each 10 points connected by a line........... 201

G-19 Probability of a given percent removal of standard plate count for specific percent removal of turbidity. Data from Table A-1 and plotted in Figure G-18.............. 202

G-20 Observations of percent reoval of particles with corresponding percent removal of turbidity. Data were obtained from Table A-1. The solid points show the median for each 10 points connected by a line............... 203

Figure Page

G-21 Probability of a given percent removal of particles for specific percent removal of turbidity. Data from Table A-1 and plotted in Figure G-20........................ 204

H-1 Effluent-turbidity vs time using 0.5 mg/l of Magnifloc 573-C. Familiarization testing............................. 206

H-2 Effluent-turbidity vs time using 0.5 mg/l of Magnifloc 572-C. Familiarization testing............................. 206

H-3 Effluent-turbidity vs time using 1.5 mg/l of Magnifloc 573-C. Familiarization testing............................. 207

H-4 Effluent-turbidity vs time using 1.5 mg/l of Magnifloc 572-C. Familiarization testing............................. 207

H-5 Effluent-turbidity vs time using 3.8 mg/l of Magnifloc 573-C. Familiarization testing............................. 208

H-6 Effluent-turbidity vs time using 3.8 mg/l of Magnifloc 572-C. Familiarization testing............................. 208

H-7 Effluent-turbidity vs time using 6.7 mg/l of Nalco 8181 (non-ionic polymer). Familiarization testing............... 209

H-8 Effluent-turbidity vs time using 4.3 mg/l of Nalco 8102. Familiarization testing...................................... 209

H-9 Effluent-turbidity vs time using 8.0 mg/l of Nalco 8102. Familiarization testing...................................... 210

H-10 Effluent-turbidity vs time using 10.5 mg/l of Nalco 8102. Familiarization testing...................................... 210

H-11 Effluent-turbidity vs time using 0.9 mg/l of Nalco 8101. Familiarization testing...................................... 211

H-12 Effluent-turbidity vs time using 6.7 mg/l of Magnifloc 572-C. Familiarization testing............................. 211

H-13 Effluent turbidity vs dose of Magnifloc 573-C. Horsetooth water.. 213

H-14 Effluent turbidity vs dose of Nalco 8102. Horsetooth water.. 213

H-15 Effluent turbidity vs dose of Magnifloc 572-C. Horsetooth water.. 214

Figure | Page

H-16 Effluent turbidity vs dose of alum as $Al_2(SO_4)_3 \cdot 14H_2O$. Horsetooth water.. 214

H-17 Percent removal of turbidity vs percent removal of *Giardia* cysts. Horsetooth water. Raw water characteristics were 7.0 NTU and temperature 10-12°C.............................. 215

H-18 Percent removal of coliform bacteria vs percent removal of *Giardia* cysts. Horsetooth water. Raw water characteristics were 7.0 NTU and 10-12°C.................... 215

H-19 Percent removal of turbidity vs percent removal of coliform bacteria. Horsetooth water. Raw water characteristics were 7.0 NTU and 10-12°C.................................. 216

H-20 Effluent coliform bacteria concentrations vs time. Horsetooth water.. 216

H-21 Headloss and effluent turbidity vs time for Run 78. Raw water was 7.0 NTU, and 6°C. Nalco 8102 doese used was 3.5 mg/l.. 217

H-22 Effluent turbidity vs Magnifloc 572-C dose. Horsetooth water.. 220

H-23 Effluent turbidity vs time for spring runoff water using 6.5 mg/l of Magnifloc 572-C................................. 220

H-24 Effluent turbidity vs time for spring runoff water using 9.0 mg/l of Magnifloc 572-C................................. 221

H-25 Headloss vs time without coagulation. Spring runoff water; raw water was 35 NTU................................. 221

H-26 Headloss and effluent turbidity vs time. Spring runoff water using 7 mg/l of Magnifloc 572-C; raw water was 16 NTU... 222

H-27 Headloss and effluent turbidity vs time during spring runoff using 12.5 mg/l of Magnifloc 572-C; raw water was 35 NTU... 222

I-1 Equivalent expressions of alum in Allied Chemical Commerical liquid alum based upon molecular weight conversions.. 233

J-1 *Giardia* analysis record form.................................. 254

ACKNOWLEDGMENTS

Completing the work reported here involved the cooperation and assistance of many individuals. Dr. Charles Hibler, Professor of Pathology at Colorado State University, completed the analyses of all samples for determining concentrations of Giardia cysts. He was assisted by Concetta Helmick and Donna Howell. Donna Howell performed most of the bacteria analyses. Dr. Gary S. Logsdon was the U.S. Environmental Protection Agency Project Officer. The late Dr. Summer Morrison was project consultant on microbiology. Dr. E. R. Baumann visited the project in June 1982 as a project consultant. Dr. Hariharan K. Iyer, Statistics Department at Colorado State University provided advice and guidance on handling the statistical analyses of data.

Shop support at the Engineering Research Center was under the direction of Walt Patzer. Word processing was under the direction of Sandy Page. The final draft was typed by Sandy Page. Drafting was done by Hanae Akari and Kenneth Streeb.

We appreciate the help of Fred Jones, Superintendent of Fort Collins Water Treatment Plant No. 1, and Kevin Gertig and other staff at Plant No. 1. Many other persons were involved in various ways.

Reviews were provided by EPA staff in Cincinnati. These included technical, editorial, and format reviews.

SECTION 1

INTRODUCTION

CONTEXT OF RESEARCH

In recent years giardiasis has been recognized as a water-borne disease of national importance. Most of the outbreaks have been traced to *Giardia lamblia* cysts in drinking water, which have been associated with ineffective water treatment. Colorado is one of the states in which the disease is endemic and where outbreaks of giardiasis have been frequent, particularly in small mountain communities. Outbreaks have been reported in other states with increasing frequency as awareness of the problem has increased.

Concern developed at Colorado State University (CSU) in 1979 following investigations were conducted by the Colorado Health Department, particularly those of Blair (1980). From this concern and an awareness of the growing extent of the problem nationally by the U.S. Environmental Protection Agency (EPA), an EPA-CSU Cooperative Agreement was developed entitled, "Removal of *Giardia lamblia* from Water Supplies - Appropriate Water Treatment for Small Systems." It should be noted also that the organism *Giardia lamblia* could be classified as a specific contaminant as defined by PL93-523, the Safe Drinking Water Act and is therefore of regulatory concern to EPA in its administration of the Act.

The overall project encompassed evaluation of three water treatment technologies--slow sand filtration, diatomaceous earth filtration, and rapid-rate filtration. Previous reports by Bellamy et al. (1984) and Lange et al. (1984) have given results of research on removal of *Giardia* cysts by slow sand filtration and diatomaceous earth filtration, respectively.

This volume evaluates the use of rapid-rate filtration with respect to ascertaining design and operating conditions for removal of *Giardia lamblia* cysts. Special emphasis was given to operation under low-turbidity, low-temperature water conditions such as that found in the ambient water supplies of the Rocky Mountain Region. At the same time, there was interest in determining whether a surrogate measure could be found for removing *Giardia* cysts.

INVESTIGATION

Purpose

The purpose of this research was to determine how to remove Giardia lamblia cysts from water supplies by rapid-rate filtration for conditions prevailing in the Rocky Mountain Region. Here raw water turbidity is less than 1 NTU during fall and winter seasons, and temperatures approach $0^{\circ}C$ during winter. The problem reduces to one of determining how to make the process effective for conditions of low turbidity and temperature.

Objectives

The objectives of this research were as follows: (1) to determine how to chemically pretreat low-turbidity, low-temperature water for efficient rapid-rate filtration, (2) to evaluate percent removals of turbidity, standard plate count bacteria, total coliform bacteria, particles, and Giardia cysts under various conditions of chemical pretreatment for low-turbidity, low-temperature water, (3) to determine the respective roles of process variables on removal efficiencies of the above parameters, and (4) to ascertain whether a surrogate indicator could be found to assess the percent removal of Giardia lamblia cysts by rapid rate filtration. Surrogate indicators investigated in the fourth objective included percent removals of turbidity, standard plate count bacteria, total coliform bacteria, and particles.

Process variables investigated in the third objective included: chemical pretreatment conditions (coagulants used, dosages of coagulants, sequence of coagulant addition), mode of filtration ("in-line" versus "direct"), media (single versus dual), filtration rate, temperature, and run time.

Scope

In the rapid rate filtration process, there are numerous variables that determine effectiveness. They include: water characteristics such as temperature, turbidity, alkalinity; chemical pretreatment conditions such as primary coagulant used, secondary coagulant used, dosages of each, and mixing intensity and detention times in both rapid mix and flocculation, and whether settling is used; and filter conditions such as filtration rate, and media. There are no mathematical models existing to consolidate these variables. Thus to ascertain relationships, empirical testing must be done to find relationships of interest, using a physical model (a pilot plant). Thus the research was experimental and utilized two pilot plants: (1) a laboratory-scale rapid rate filtration pilot plant, and (2) a field-scale 1.3-l/s (20 gpm) rapid rate filtration pilot plant.

With so many variables, tens of thousands of tests could be conducted. Therefore the method of this research was to maintain constant many of the above variables and to vary the others over limited ranges. Thus raw water conditions used were restricted to those found in the Rocky Mountain Region during fall and winter seasons, e.g. low turbidity. Some initial "familiarization testing" was conducted with both pilot plants, however, using Horsetooth Reservoir water which has turbidity levels of 5 to 10 NTU. Since this water is more easily treatable it was used to develop testing procedures. The investigation of temperature effect at the lab-scale used only two temperatures, 3°C and 18°C. Colder temperatures with the lab-scale pilot plant were not possible because of ice formation at lower temperatures. With the field-scale pilot plant temperature could not be controlled and so operation was at ambient temperatures, which reached 0°C. Hundreds of commercial polymers are available, but screening was conducted only until effective ones were found.

Even with such restrictions a total of 178 test runs were conducted using the lab-scale pilot plant over an 18 month period. Using the field-scale pilot plant 131 test runs were conducted, with 31 of these using raw water having turbidity level of less than 1 NTU. The approach was to use the lab-scale pilot plant to ascertain functional relationships and the field-scale pilot plant to confirm these findings for ambient conditions.

Significance

Outbreaks of giardiasis due to water borne transmission of *Giardia lamblia* cysts in drinking water are a national problem. The treatment technology associated with virtually all of the outbreaks has been rapid rate filtration.

While deficiencies in the operation or design of the rapid rate filtration process have not been ascribed definitively, many outbreaks have occurred under conditions of no chemical pretreatment. In this mode of operation, i.e. without chemical pretreatment, the filter media acts merely as a "strainer."

The practice of using no chemicals is common in the Rocky Mountain Region during fall and winter seasons when raw water turbidities of mountain streams are less than 1 NTU. In addition, coliform counts of these waters are low, e.g. 100 per 100 mL. Also during winter, temperatures will approach zero degrees Celsius.

There are three basic problems associated with such conditions. First, raw water turbidity levels already meet drinking water standards, and the low coliform counts can be handled easily by disinfection. Thus there is a general lack of perception that a problem exists. Second, effective coagulation and filtration under such conditions, e.g. low turbidity, low temperature, is simply beyond the state-of-the-art of knowledge about the rapid rate filtration process. This is not to say that low turbidity waters have not been filtered successfully. An example is at Duluth as described by Black and Veatch (1975) (Logsdon et al., 1983) and Schleppenback (1984), where water from Lake Superior, having less than 1 NTU turbidity, has been filtered to remove asbestos fibers. Also Kirmeyer (1979) described filtration of low turbidity waters from the Tolt River in Washington. Such cases notwithstanding, it is true generally that knowing what to do is not clear, even if there is perception that a problem exists. And third, since the ambient turbidities and coliform counts are so low, there is question on how to evaluate the effectiveness of the filtration process.

To better ascertain how to treat this low turbidity, low temperature, water by the rapid rate filtration process would both advance the state-of-the-art of the process and at the same time provide the knowledge needed to remove Giardia cysts, a major national problem. In addition, with many communities using the rapid rate filtration process, advancement of the state-of-the-art of practice will permit these plants to improve the overall level of health protection. This will make cost-effective a large aggregate amount of capital investment in existing plants. The documented outbreaks of giardiasis associated with low turbidity waters demonstrate that filtration merely to meet the 1 NTU standard is not adequate to protect public health.

GIARDIASIS

The disease giardiasis has been recognized world wide over recent years. It is prevalent in Russia, particularly in Leningrad (Brodsky et al., 1974). In the United States, the first documented water borne outbreak was in Aspen, Colorado during the winter of 1965-66. A survey of 1094 skiers who had vacationed in Aspen showed that 123 (11 percent) had developed symptoms similar to giardiasis (Craun, 1979). Outbreaks have occurred most frequently in the Rocky Mountains, in the Northwest, and in the Northeast. Visvesvara and Healy (1978) estimate three to seven percent of the adult population harbor the parasite. Colorado is one of the states where the disease is endemic. Outbreaks have been reported in Aspen, Vail, Boulder, Estes Park, Hideway Park, etc. (Davies and Hibler, 1978), and recently in Purgatory (Colorado Disease Bulletin, March 31, 1984). Blair (1979, 1980) has investigated outbreaks at Estes Park and Vail, where rapid rate filtration was used, and recovered Giardia cysts from filtered water. An outbreak occurred at Empire, Colorado in 1981; the town used chlorination but no other treatment. The most recent Colorado outbreak was at Purgatory, in January 1984. Chlorine was the only treatment in this case, but it is notable that levels were maintained at about 2.5 mg/L (Colorado Disease Bulletin, March 31, 1984) with about 4 hours detention time (Blair, 1984, personal communication).

In the Northwest the first documented outbreak was in 1976 in Camas, Washington (Pluntze, 1983). Some 600 persons or about 10-15 percent of the population, were affected. The source of infection was found to be beavers. Leavenworth, Washington had a similar outbreak in 1980, also reported by Pluntze, which affected 27 percent of the population, or 578 persons. In these cases the water was treated by rapid rate filtration.

One of the largest outbreaks of giardiasis occurred in Rome, New York from November 1974 to June 1975 (Shaw et al., 1977). A total of 350 residents had laboratory confirmed cases and an estimated 5,300 others may have been symptomatic. Chlorine was the only treatment. This was the first outbreak in which *Giardia lamblia* cysts were recovered from a municipal water supply.

The disease has been reported also in Banff National Park by DeWalle and Jansson (1983), where 121 confirmed cases occurred in the winter of 1981-82. It has become a major concern in Alberta and in British Columbia. In November 1983 the British Columbia Water and Wastes Association held a seminar on the topic to convene those having knowledge and interest about the problem (British Columbia Water and Wastes Association, 1983). Cleasby (1983) reported that at Bradford, Pennsylvania in 1979 an estimated 2900 persons were affected. During recent months, since the fall 1983, further outbreaks have been reported at Houtzdale, Pittston, and McKeesport in Pennsylvania (Logsdon, 1984, personal communications).

Giardiasis is an intestinal disease caused by ingestion of cysts from the protozoan, *Giardia lamblia*. Ingestion of one to ten cysts is sufficient to cause the disease (Rendtorff, 1977). The diseae symptoms will appear with two to thirty five days after ingestion, with one to two weeks being the most common incubation period.

Giardia lamblia is a pathogenic intestinal parasite found in humans and in other warm blooded animals. The beaver has been thought to be a common source of cysts, but Hibler (1979) has reported recovery of cysts from a wide variety of wild animals. Recently, Hibler (personal communication, 1984) has indicated the muskrat may be a major source cysts found in streams. In addition dogs are commonly infected (and have served as the source of cysts for this research).

The organism *Giardia lamblia* has two life stages, a reproductive trophozoite stage, and a dormant cyst stage. The cysts, which are the form found in the environment, are about 7 to 12 micrometers in their smallest dimension, and can survive about two months in cold water (Hibler, 1984, personal communication). Upon ingestion the cyst becomes a trophozoite and attaches to the lining of the small intestine. Figure 1 shows drawings of both cyst and trophozoite, with dimensions indicated.

There are at least two morphologically different species of *Giardia*, *Giardia lamblia* and *Giardia muris*. It is not certain among researchers how many actual species exist in addition to these. Therefore species names have been ascribed to *Giardia* depending upon the host. Jakubowski (1979) has listed those with claw like median bodies to include *Giardia lamblia* (man), *Giardia canis* (dog), *Giardia cati* (cat), *Giardia bovis* (ox), etc. Those with rounded median bodies are *Giardia muris* and are found in the house mouse, rat, and hamster. Hibler (1984, personal communication) believes that the species listed in the first group are the same and may be cross transmitted between hosts of different animal species. Hibler (Davies et al., 1983) has reported self infection using *Giardia* cysts obtained from dogs. Then Hewlett et al. (1982) established that *Giardia* cysts from humans can infect dogs.

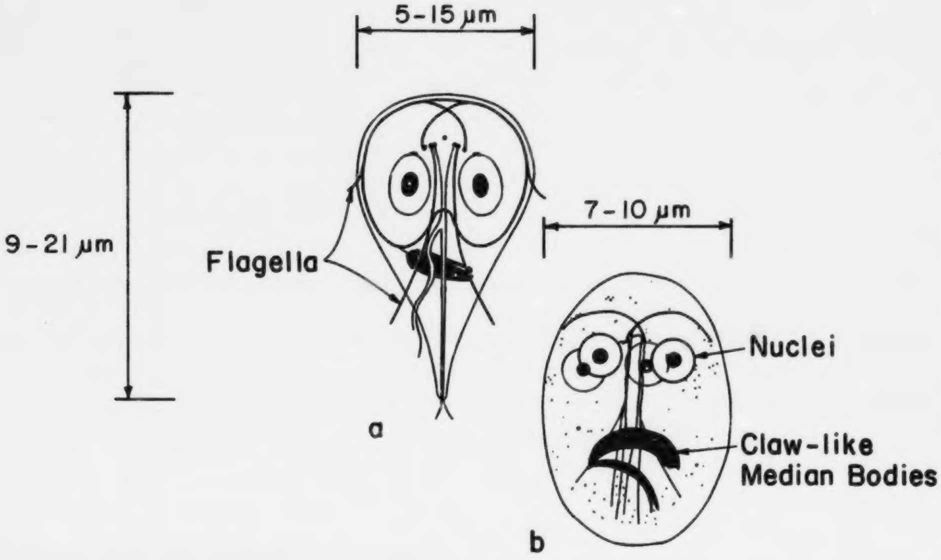


Figure 1. Sketches of a) trophozoite, and b) cyst stages of Giardia lamblia (Jackubowski and Hoff, 1979).

Thus the designation Giardia lamblia is believed proper for the Giardia cysts used in this research, which were obtained from dog fecal samples.

TREATMENT OF MOUNTAIN WATERS

Characteristics

The flows of mountain streams in the Rocky Mountain Region, and also the Sierra Nevadas in California and the Cascades in Washington have a typical "snowmelt hydrology." In other words, most of the flow volume occurs during spring runoff about mid April through June. During the summer and into the fall snowmelt continues from higher elevations at a slower rate and is complemented by base flow from aquifers. During the spring runoff period the turbidity level is nominally about 30 NTU and may even reach 200 NTU for example if a thunderstorm occurs. These waters are treatable by conventional rapid rate filtration, e.g. rapid mix, flocculation, sedimentation, and filtration, though operators may have difficulty adjusting coagulant dosages. A visible floc readily forms with proper coagulation. As the spring runoff recedes, however, the turbidity levels decline and may stabilize at 0.5 to 1 NTU from September until mid April. Temperatures will decline also, approaching zero degrees Celsius in December and January. Total dissolved solids may be very low throughout the year, e.g. nominally about 50 to 100 mg/L. Alkalinity also may be low, e.g. 40-50 mg/L as $CaCO_3$.

Table 1 illustrates showing monthly water quality for the Cache La Poudre River at the Fort Collins Water Treatment Plant No. 1, located in Poudre Canyon, about twelve miles from the city center. The table shows that average turbidity for 1980 is less than 1 NTU during six of the twelve months, and average temperature is less than 1°C during four months. The characteristics shown in Table 1 for the Cache La Poudre River, are typical of other mountain streams in the Rocky Mountains. But there are exceptions. Table 2 shows characteristics for water from Horsetooth

Table 1. Characteristics of Cache La Poudre River water for calendar year 1979 at Fort Collins Water Treatment Plant No. 1.

Cache La Poudre River, 1979			1981
Month	Temperature (°C) Average	Turbidity (NTU) Average	Total Coliform Bacteria (org/100 ml)
January	0.55	0.62	<1
February	0.55	0.63	<1
March	2.68	0.65	<1
April	8.29	3.0	100
May	9.10	9.3	8
June	10.20	6.45	—
July	15.23	2.30	198
August	14.5	4.17	96
September	14.8	1.20	77
October	9.7	0.65	82
November	0.89	0.49	10
December	0.61	0.47	4
Yearly Average	7.26	2.49	

* City of Fort Collins, Colorado, monthly data report for 1979.

Table 2. Characteristics of water from Horsetooth Reservoir during 1979 at Fort Collins Water Treatment Plant No. 1 during months of operation.1/

Horsetooth Reservoir, 1979			1981
Month	Temperature (°C) Average	Turbidity (NTU) Average	Total Coliform Bacteria (org/100 ml)
April	6.5	4.3	<1
May	7.3	4.5	<1
June	-	5.1	—
July	8.0	6.1	2
August	8.0	6.73	3
September	8.2	7.3	4
October	8.5	7.75	19
Yearly Average	7.71	5.9	

1/ City of Fort Collins, Colorado, monthly data report for 1979.

Reservoir at Fort Collins Water Treatment Plant No. 2. It shows April to October because the plant operates only during those months. Total dissolved solids are about 50 mg/L and total alkalinity is about 40 mg/L as $CaCO_3$, whole turbidity ranges between 4.3 NTU and 7.8 NTU.

Treatment Practices

During spring runoff when turbidity levels are 10 to 50 NTU nominally, conventional water treatment (rapid mix, flocculation, sedimentation, filtration) is used for waters from mountain streams. The processes of coagulation and flocculation occur as expected under these conditions, with floc formation, and effective filtration.

Under conditions of low turbidity, prevailing from September or October until April, and low temperature, e.g. November through February, coagulation is difficult. If chemicals are used it is difficult to develop a floc. For such reasons, and because the 1 NTU turbidity standard can be met even with the raw water, chemical pretreatment is often terminated during the low turbidity period. The filtration process is simply 'straining' during this mode of operation. This is of course, contrary to the concept of rapid rate filtration; chemical coagulation is an intrinsic part of the process. Along with this discussion it should be noted that some plants have used high dosages of alum,, e.g. 15 to 50 mg/L, which forms a visible floc with low turbidity water and should provide effective filtration. Others use filter aids, some of which are doubtful in their effectiveness. Another approach with low turbidity waters is to add bentonite clay to develop artificial turbidity to facilitate coagulation.

The 'straining' mode of operation likely passes small particulates and microorganisms as may be found in these low turbidity waters. Blair (1979, 1980) has reported on C. Hibler's examinations of particulate concentrates obtained from fiber filters used to sample finished waters in which chemical pretreatment was not practiced. The filters contained cysts, strongyles eggs, and nematodes. Thus Giardia cysts, bacteria, and other substances may readily pass through the filter, even though the effluent water turbidity is meeting the 1 NTU drinking water standard. Also, total coliform bacteria levels typically are less than 100 org/100 mL in these mountain waters. Thus if the coliform concentration in the finished water is only 50 org/100 mL it does not mean that effective filtration has occurred; the percent removal may have been very little. Similarly, the percent removals of turbidity are typically only 20-50 percent, e.g. from 0.5 NTU in raw water to 0.3 NTU in finished water. From this argument, a low turbidity level and a low total coliform bacteria concentration in the finished water do not indicate the water is safe for drinking. Giardia cysts, and indeed other pathogens, could be present in the finished water as various outbreaks have indicated.

Problems in Treatment

How to treat low turbidity water, e.g. water having turbidity less than 1 NTU, is insufficiently addressed in the literature, and it is not a part of the lore of practice. The basic premise of rapid rate filtration is that effective coagulation must occur, leading to a floc. If abundant, a portion of the floc must settle in a sedimentation basin so that filters are not overloaded. The residual floc is intended to penetrate the filter media where it is stored until backwash. Backwash occurs when headloss becomes excessive, or when turbidity breakthrough occurs. The floc forms more readily when charged colloidal particles are present which are neutralized by a metal ion, e.g. Al^{+++}.

In low turbidity Colorado waters, colloid particles may be less abundant, and the coagulation reaction may not occur as indicated above. The mechanisms involved are not known. Probably it is a 'sweep' coagulation that occurs, as defined by Amirtharajah and Mills (1982), if alum is used as the primary coagulant. Neither has practice evolved, since the raw waters meet the 1 NTU turbidity standard. The role of temperature is not understood either. Whether the problem of difficult coagulation is due to low turbidity or low turbidity combined with low temperature is not known.

LITERATURE REVIEW ON RAPID RATE FILTRATION

Development

The first filter to supply water to a whole town was at Paisley, Scotland, completed in 1804. This was what is termed today a 'slow sand filter.' It is a technology that spread through Europe in the nineteenth century. The first slow sand filter built in the United States was at Poughkeepsie, New York in 1872, under the supervision of James Kirkwood. By 1890 only a few had been built in the United States.

American practice evolved along a different line, which resulted in what is known today as 'rapid rate filtration.' The technology had its origins in England when in 1791 James Peacock patented the idea of a 'reverse flow wash.' This is, of course, one of the distinguishing features of rapid rate filtration as contrasted with slow sand. The method of sediment removal in the former is termed 'mechanical,' vis a vis 'manual' for latter. The technology was developed further by a succession of European patents, each providing a slight improvement, or modification. The idea of mechanical agitation by rakes and of surface wash, were among the patented ideas.

The American activity began in 1867 in St. Louis with a patent, on a filter similar to Peacock's, by Henry Flad. In 1880 Daniel Otis in New York patented a filter with backwash, surface wash, and mechanical rakes.

In 1885 another basic distinguishing feature, chemical coagulation, was added to the rapid rate filtration technology. Col. L. H. Gardner, Superintendent of the New Orleans Water Co. conducted small-scale experiments on coagulation to clarify the muddy waters of the Mississippi River. At the same time Isaiah Hyatt, working on an industrial water supply using raw water from the same source, acted upon Gardner's suggestion to try a coagulant, perchloride of iron. Hyatt made a revolutionary advance, however, by combining this with filtration, using filters sold by the Newark Filtering

Company. In 1885 this new technology was first applied to a municipal water supply in Somerville, New Jersey. Hyatt claimed that by 1888 the technology had been adopted by some 30 towns.

By 1890 many commercial filter manufacturing companies had entered the market, each with its own patented variation of the same theme. Most of these filters were pressurized, and were premanufactured.

In 1891 the National Water Purifying Co. contracted with the City of New Orleans to supply clear water from the Mississippi River, for one of the largest mechanical filtration plants ever built. The plant used coagulation and filtration with no provision to first settle the sediment-laden waters of the Mississippi. The plant was a spectacular failure and the company could not fulfill its contract. Later the City of New Orleans took over operation and built what is called today a pilot plant, under the direction of Robert S. Weston, to learn how to treat these waters. From this work a 40 mgd water treatment plant, comprised of sedimentation, coagulation and filtration, was designed and put in operation in 1909.

The first comprehensive studies of the rapid rate filtration process were conducted by George W. Fuller. In 1895-97 the city of Louisville, Kentucky engaged Fuller, and others, to examine several patented processes including three makes of filters. This was after some 20 years of searching by Louisville for an effective filtration technology to treat the waters of the Ohio River. The greatest lesson of the Louisville experiments was to underline the important role of presedimentation and precoagulation in the operation of mechanical filters treating highly turbid waters. Cleasby (1981) credits Fuller with establishing the hydraulic loading rate criterion of 2 gpm/ft^2 (8.3 cm/min), which was adopted by virtually all state health departments and has remained almost inviolate until recent years. Fuller also acknowledged that without adequate chemical pretreatment, there is no assurance of acceptable water.

A new era in design of the mechanical filters was launched in 1902 when a 34 mgd mechanical filtration plant, designed by George W. Fuller, was placed in operation at Little Falls, New Jersey. In shape the filters were rectangular rather than round, and in structure they were reinforced concrete rather than wood or iron. Also the coagulants were added not at the point of entry of the water into the filter, but at the point of entry into a detention basin, to permit coagulation and flocculation (evidently without mechanical mixing). Also air scour was used in this plant.

At this point, which began really after the work at Louisville, the modern era of rapid rate filtration began. The technology was firmly established in the United States, and slow sand filtration never gained a strong foothold.

Later, by 1920, both baffle basins for rapid mix, and paddle wheel flocculation basins were used. These are mentioned by Langlier (1921), which is notable also because the idea of the classic jar-test was introduced in the same article.

Rapid rate filtration technology was studied further in the 1930's by Baylis at Chicago, together with Hudson (Baylis et al, 1971, and Hudson, 1981). Baylis showed that floc penetrates into the sand media, but that the amount of penetration depends upon the character of the floc. He showed also that finished water quality did not deteriorate with hydraulic loading rates as high as 5 gpm/ft^2 (24 cm/min).

The next substantial innovation was the introduction of dual media filtration, e.g. coarse anthracite and sand (Conley, 1961). The idea was to permit the chemical floc to penetrate into the filter, in accordance with the concepts by Baylis, and thus to permit longer filter runs. At this time the idea of high hydraulic loading rates, e.g. 5 gpm/ft^2 (24 cm/min) and even 8 gpm/ft^2 (33 cm/min), was further confirmed and reinforced. Stimulated by this work, higher rates were introduced into practice and were an established concept by the 1970's.

Principles

The basic premises of rapid rate filtration are based upon removal of turbidity from raw water so that the water is both safe and palatable for drinking. Usually if turbidity removal occurs, such that drinking water standards are met, significant removals of bacteria, viruses, cysts, etc. will occur also.

Turbidity is a measure of the light scattering intensity of colloidal suspended particles. According to Black (1948), to remove these colloids, their negative charges must be neutralized. This is possible by addition of a metal salt to the water such as $Al_2(SO_4)_3$ or $FeCl_3$, to provide a charge neutralizing cation, such as Al^{+++} or Fe^{+++}. This action 'destabilizes' the colloidal suspension and permits aggolmeration. Stumm and O'Melia (1968) have added further basic concepts to coagulation theory, pointing out that adsorption of coagulants plays a key role in the process. Coagulation of low turbidity waters is addressed in terms of 'sweep' coagulation. This has been described further by Amirtharajah and Mills (1982). In the process of 'sweep' coagulation, a metal precipitate forms as a crystal, which may, according to Edzwald (1981), enmesh the destabilized colloid, as for example $Al(OH)_3$. All of this is termed 'coagulation.' The terms are defined further by Hudson and Wolfner (1967) as 'the process of chemical reaction of the coagulant in water.' The rapid mix basin then has the purpose of bringing the reactants in contact. The rate of the reaction is proportional to the number of contacts per unit time, which is proportional to the mixing intensity, G (sec^{-1}), and the detention time, T, in the basin.

The crystals must grow in size to permit formation of a 'floc.' This occurs by slow agitation in a flocculation basin. The agitation is turbulence, which has the function of promoting contacts between particles. The objective of flocculation is to cause the floc to grow sufficient in size so that the floc suspension may be settled or filtered.

Usually, in most waters, the floc is abundant so that if all of it is permitted to reach the filters, the rate of headloss would be very high, thus reducing the run length. For this reason, sediment basins are used before filtration to reduce the solids loading on the filter.

The filtration step is intended to remove the floc by permitting penetration of it into the filter bed. Here the characteristics of the floc are important. It is often described as being "tough," "strong," "pin point," "fragile," etc. According to Hudson (1981) if a large "strong" floc reaches the filter bed there may be little floc penetration, and very short filter runs. The floc will merely accumulate on the surface of the filter bed.

The above treatment train, i.e., rapid mix, flocculation, sdimentation, filtration, is termed "conventional" filtration. The beginning of this idea was described by Fuller in 1897 (as reported by M. N. Baker, 1949), who states, "The evidence is very decisive that so far as practicable the suspended matter should be removed before reaching the sand layer, and that, at that point, the water should be thoroughly coagulated. Further it is clear that subsidence should be employed with waters of this character to a degree where the amount of coagulant to be applied just before the entrance to the filter should not frequently exceed 2 grains per gallon."

Modern Theory

While modern practice began after the work of Fuller and his co-workers in 1897, modern theory began in the 1960's. Black (1948) provided the beginning, incorporating concepts of colloid chemistry as a basis for explaining coagulation. Langlier and Ludwig (1952) showed empirically, by jar tests, the role of pH and alum dosage on settled water turbidity, and the role of cation exchange capacity of the colloids.

In an effort to develop a more scientific basis for determining coagulant dosage, Black (1958, 1961, 1962), and Riddick (1961) introduced the idea of zeta potential. Instrumentation has been developed to measure zeta potential but the technique is not used widely.

The use of polymers as "coagulant aids" and as "filter aids" began about 1960 (Pugh and Heller, 1960). O'Melia (1969) has described the mechanisms concerning how the polymers interact with metal-ion flocs.

Coagulation theory began to develop a true scientific sophistication with the work of Stumm and Morgan (1962). This has been developed further by Stumm and O'Melia (1968) and by Stumm (1977). Also Ives (1977) conducted a NATO Advanced Study Institute, in which various persons developing coagulation theory were convened. Ives (1975) also conducted such an institute on the subject of filtration.

Ives' work on filtration (1961) was the beginning of modern filtration theory. Here he has introduced the idea of surface forces between the sand media and the particles to be removed. Camp (1964) has demonstrated also that floc will attach to sand grains and indeed coat them. This deviates from (or adds to) the concept that discrete floc particles enter the filter and remain intact. At the same time, Cleasby and Baumann (1962) have worked continuously on the topic of filtration. They state that, 'the surface cake only develops where filtering a suspension that has a strong tendency to be removed at the surface, a suspension in which the particles have adequate internal strength to resisting the hydraulic shear force tending to wash them down into the filter.' From this the idea is further reinforced that the nature of the filtration process is dependent upon the kind of coagulation that has occurred.

Recent work has been directed toward 'direct filtration,' as described by Logsdon (1978, 1983) and Tate et al. (1977). This mode of filtration, defined as coagulation, flocculation, filtration, has been advocated in recent years for water having turbidity levels of less than about 30 NTU nominally.

The role of process variables has been investigated by Cleasby (1962) and Roebeck (1964). These investigations have been experimental.

Filtration of Low Turbidity Waters

The treatment of low turbidity waters has seldom been a specific concern in either theory or practice. Since the raw water may already have turbidity levels of less than 1 NTU, which meets the standard, there has been little impetus to understand treatment. Even with the preoccupation with removal of Giardia cysts, the concern has been to control the symptom rather than the cause. Indeed water treatment plants are designed usually toward the more severe turbidity problems occurring during spring runoff.

Some have reported handling of treatment problems involving low turbidity waters. These include the work at Lake Superior, related to removal of asbestos fibers, where raw water having less than 1 NTU turbidity was treated to produce a finished water of about 0.05 NTU and at Seattle where low turbidity Tolt River water was treated (Logsdon et al., 1983). DeWalle et al. (1984) have reported on treating waters having raw water turbidities of 1 to 5 NTU. They have shown that at the Hoquiam Water Treatment Plant, turbidity reductions of 90 percent are possible using alum treatment with 4 NTU raw water, but only 20 to 50 percent is possible using alum treatment when raw water turbidity is only 1 NTU. Without chemical pretreatment turbidity reduction is only 10 to 50 percent with 1 NTU raw water.

Effect of Temperature

Brief and scant information appears in the literature about the effect of temperature on coagulation and filtration. Most of the literature relates the temperature effect on pH, and the density and viscosity of water, as factors in floc formation. Conflicting conclusions concerning the effect of temperature on floc formation using alum or iron salts is drawn by past reseachers. Leipold (1934) found that temperaure change has no effect on floc formation or flocculation. Velz (1934) concluded that an increase in temperature required an increase of coagulant, and that a decrease in temperature permitted a decrease in the amount of coagulant to produce the same result. Both of these findings are in conflict with the results by Mohtadi and Rao (1973) who studied the temperature effect on flocculation for synthetically prepared water. They found the decreasing water temperature required an increase in alum dosage to achieve the same degree of flocculation. Mohtadi and Rao found that a given degree of flocculation can be achieved with the same quantity of flocculant at different temperatures provided the flocculation is carried out at the optimum pH value. This confirms a similar finding by Camp et al. (1940).

In winter, mountain region surface waters are low in both temperature and turbidity. Operators often complain of difficulty in treating such waters. It is not known if this difficulty is due to the temperature effect or because of low turbidity influent water, or both. Because of such difficulty in treating this water and because the raw waters have turbidity levels less than 1 NTU, it is common practice to omit chemical pretreatment. The filter media acts as a strainer only and most likely passes microorganisms such as Giardia cysts (Logsdon, 1981).

To sum up, very little has been done to explore the effect of temperature on coagulation and filtration. Whether winter treatment difficulties are due to low temperature, or low turbidity, or both, is not addressed in the literature.

Filtration of Giardia Cysts

Logsdon (1981) reports that after reviewing the literature he found '...no research on water filtration for Giardia cyst removal.' Logsdon (1981) states also, that filtration studies of the 1930's and 1940's were, however, conducted for removing Entamoeba histolytica cysts.

SECTION 2

SUMMARY AND CONCLUSIONS

Removal of Giardia cysts by rapid rate filtration is associated with effective operation of the process itself, and not with any particular technique of operation. The fact that Giardia cysts have passed through water treatment plants employing rapid rate filtration is indicative of the fact that effective operation may not be occurring. Usually these cases have occurred in plants using raw water having low temperature and low turbidity. Difficulty in attaining effective operation under such conditions is believed, in this work, to be an industry generic problem. Thus to understand the factors influencing removal of Giardia cysts by rapid rate filtration requires a more comprehensive understanding of how to make the process more effective for low temperature, low turbidity raw waters, in general. Results are summarized in terms of percent removals of various parameters, e.g. Giardia cysts, total coliform bacteria, standard plate count bacteria, and turbidity. Then the effects of process variables on removals are reviewed. These include coagulants, dosages, mode of filtration, media, filtration rate, temperature, etc.

The experimental work was conducted using a laboratory-scale rapid rate filtration pilot plant, and involved 178 experimental test runs. To confirm the findings from the lab-scale pilot plant, the field-scale pilot plant was operated under a more limited range of conditions, e.g. coagulants and dosages were preselected, hydraulic loading rate was fixed, etc. Some 131 test runs were conducted using the field-scale pilot plant, with 31 using low turbidity water. Work with this pilot plant also examined Giardia removal efficiencies using water from Horsetooth Reservoir, which had turbidity levels of 5 to 10 NTU.

The sections following summarize the findings and conclusions of the research. First the findings relative to polymer selection for treatment of low-turbidity, low-temperature water are reviewed. Removal efficiencies are discussed second, and then the influences of process variables on removals are described. Finally the explorations concerning the use of surrogate indicators for Giardia cyst removal are reviewed.

CHEMICAL PRETREATMENT

The search for chemical coagulants focused on the use of polymers, to be used in conjunction with alum. Two polymers, Magnifloc 572C R and Magnifloc 573C®, were found to be highly effective in treating low turbidity, low temperature water. Ten were tested and the others were found to be not effective for the low turbidity, low temperature conditions. Effectiveness was judged initially using turbidity removal as the measure. Based upon these results further testing was done to determine removals of bacteria and Giardia cysts.

The results show that it is feasible to treat effectively low turbidity, low temperature water by means of rapid rate filtration. To attain effective treatment polymer selection is critical and must be based upon screening, using turbidity removal as a measure of effectiveness. Determination of the range of effective dosages of alum and polymer requires additional testing.

REMOVALS

Removals of the five parameters tested were affected most by chemical pretreatment. With no chemical pretreatment percent removals varied from nearly zero to about 70 percent. With "nonoptimum" chemical pretreatment percent removals were more variable, but in general, improved only slightly. Using "optimum" chemical pretreatment, however, removals of turbidity consistently exceeded 80 percent, and removals of bacteria and Giardia cysts always exceeded 95 percent, with many removals more than 99 percent. These findings were corroborated by the field-scale testing.

These results again underline the importance of chemical pretreatment in rapid rate filtration. With no chemical pretreatment the process cannot be expected to provide an effective barrier to the passage of pathogens when they occur in the raw water supply. With proper chemical pretreatment, however, removals of bacteria and Giardia cysts can be expected to exceed 95 percent.

PROCESS VARIABLES

Process variables investigated included chemical pretreatment variables such as coagulant selection, dosages of coagulants, and sequence of coagulant additions, and mode of process train, i.e. "in-line" or "direct." Also, investigated were the use of both single media and dual media, filtration rate, temperature, and run time. All of this was done using the lab-scale pilot plant.

Coagulant Selection

Ten polymers were tested with respect to effectiveness in turbidity removals for low turbidity waters. They were tested as primary coagulants, as coagulant aids with alum, and two were tested as filter aids. The filter aid polymers were found to be not effective with results about the same as when no chemicals were used. Two coagulant aids, Magnifloc 572C R and Magnifloc 573C R , were found to produce turbidity removals generally over 80 percent when used with alum. Removals of bacteria and Giardia cysts exceeded 95 percent when using these polymers as coagulant aids. Results with the other polymers were more variable.

Dosages of Coagulants

The "surface" of percent turbidity removal was "mapped" as a function of alum dosage and polymer dosage, using Magnifloc 572C R. The "mapping" showed that the polymer alone is not effective, nor was alum alone (except at dosages of about 40 mg/L). With only a small alum dosage, however, e.g. about 2 to 5 mg/L, 1 to 2 mg/L of polymer was effective in reducing turbidity levels from <1 NTU to as low as 0.05 NTU. This surface remained relatively flat at 0.05 NTU or at 0.1 NTU, for alum-polymer dosages in any combination up to 20 mg/L alum and 8 mg/L polymer. Removals of bacteria and Giardia cysts exceeded about 95 percent, and more frequently than not exceeded 99 percent, for dosage combinations which gave the highest percent removal of turbidity. The "optimum" dose was deemed to be the lowest certain to give the highest turbidity removal efficiency. This was the approximate dose range used for the field-scale testing.

Field-Scale Testing of Coagulants

Filtration Without Coagulation--

The results of the field-scale testing also confirmed the necessary role of chemical pretreatment in effective filtration of low-turbidity water. Tests with the WATER BOY showed that without chemical pretreatment, i.e. a coagulant dosage of "none", large numbers of Giardia cysts and coliform bacteria passed through the filter, while turbidity removals were only about 10 percent. This was shown for two waters, Horsetooth Reservoir water having turbidity levels of 5 to 10 NTU, and Cache La Poudre River water having turbidity levels of <1 NTU.

Coagulation of Horsetooth Reservoir Water--

The field results showed that when using Horsetooth Reservoir water all polymers tested, either alone or with alum, were highly effective, e.g. >90 percent removals occurred for Giardia cysts and coliform bacteria, and removals were often >99 percent. Removals were equally high for both "nonoptimum" coagulant dosages and for "optimum" coagulant dosages. Thus removals were not highly sensitive to differences in polymers or to dosages of a given polymer for this water.

Coagulation of Cache La Poudre River Water--

Results for testing using water from the Cache La Poudre River showed that only one chemical combination tested, Magnifloc 572-C used with alum, was effective in coagulation for filtration of low-turbidity water. For this combination at "optimum" dose removals were >94 percent for both Giardia cysts and coliform bacteria. Removals for the "nonoptimum" dosages, or removals with other coagulants, were about the same as for the "none" coagulant dosage condition, e.g. removals were only 30 percent nominally. These findings underline the importance of coagulant selection and dose determination when filtering low-turbidity waters, i.e. those having turbidity levels less than 1 NTU.

Sequence of Coagulant Additions

Generally in practice, if a two stage rapid mix is used, alum is added in the first stage and polymer is added in the second stage. Alternatively, both may be added simultaneously in one basin.

The results showed that effluent turbidity levels from the filters were the same whether alum and polymer added in sequence or simultaneously. Filtered water turbidity levels were noticeably higher, however, for the polymer-alum sequence.

These results show that a single basin, with both alum and polymer added simultaneously, is as effective as the use of two basins in sequence. Pilot testing should be conducted, however, as each water is unique.

Mode of Filtration

Two modes of filtration were investigated, "in-line" and "direct." Removals of turbidity were the same for both modes when using raw water having turbidity levels of less than 1 NTU. In-line filtration was tested also for waters having turbidity as much as 14 NTU. While turbidity removal efficiency was high, headloss increased rapidly, which would indicate short filter runs.

Water treatment plants could be designed to permit use of "in-line" filtration over the period when turbidity levels are about 1 NTU, which may extend from about August to April in the Rocky Mountain Region. Again, pilot testing should be conducted. Such plant should be designed for flexible operation, to permit "in-line" filtration when raw water turbidities are low, with "direct" filtration as another option, and conventional filtration for the high turbidity spring runoff conditions.

Comparison of Media

The use of both single media and dual media was compared with respect to turbidity removal. Turbidity removals were the same for both media for several conditions of chemical pretreatment, including no chemicals. The initial headloss for single media was appreciably higher, however, than for dual media, e.g. 11 cm Hg versus 6 cm Hg. This difference can be accounted for by the differences in sand depth. The rate of headloss increase was higher also for the single media.

These results showed that both sand and dual media have the same effectiveness in removal of turbidity. The appreciably higher headloss and higher rate of increase of headloss seen in the sand filter confirm that a single media filter is not attractive as an alternative for practice.

Filtration Rate

Removals of turbidity, bacteria, and Giardia cysts were measured for filtration rates of 8, 20, 32, and 41 cm/min (e.g. 2, 5, 8, and 10 gpm/ft^2).

All removals were high ranging from 90 percent for turbidity to 99 percent for total coliform bacteria, and showed no appreciable change in percent removals for filtration rates of 8, 20, and 32 cm/min. A noticeable decline was seen, however, for the filtration rate of 41 cm/min.

Thus, for filtration of low turbidity waters, the rate of filtration up to 32 cm/min has little effect on pecent removals. If higher rates are contemplated, pilot testing should be conducted.

Temperature

Pairs of tests were conducted at $5^{o}C$ and at $18^{o}C$ for identical conditions. Four such pairs of tests were conducted for four different coagulant dosages. Percent removals were measured for turbidity, standard plate count bacteria, and total coliform bacteria. The data are not conclusive. Some pairs show almost identical removals between the two temperatures, while others show an appreciable difference. Further experimental work is warranted.

Run Time

Removals of turbidity, standard plate count bacteria, total coliform bacteria and *Giardia* cysts were measured at "run times" of 30 min and at 90 min. There were not appreciable differences in percent removals for the two "run times." Percent removal of turbidity was seen to increase sharply from zero minutes to 30 minutes and to remain about the same thereafter. The noticeable change in the 0-30 min period was due to the time required for coagulated water to travel from the rapid mix basin to the filter effluent. Filter to waste would be warranted only to insure that the coagulated water is in contact with the filter, vis-a-vis in treated water used in backwash. Mixing of coagulated water with backwash water would cause a nonoptimum dosage to be applied to the filter.

SURROGATE INDICATORS OF GIARDIA REMOVAL

Exploration of relationships between the dependent variables, e.g. turbidity, standard plate count bacteria, total coliform bacteria, particles, and *Giardia* cysts, was done by means of plots and statistical analyses. All of the above dependent variables (except *Giardia* cysts) were examined to determine if a relation existed between percent removal of the given parameter and percent removal of *Giardia* cysts. Histogram plots showed definite relationships, e.g. high percent removals of turbidity were associated with high percent removals of *Giardia* cysts. Statistical tests, e.g. the student t-distribution, showed 99.5 percent confidence levels, indicating that functional relationships exist between removals of the above parameters and removals of *Giardia* cysts.

All parameters examined were found to be suitable as indicators of percent removal of *Giardia* cysts by rapid rate filtration. Turbidity is recommended because it is easy to use. In general, if 70 percent turbidity removal is achieved, then there is 0.85 probability that removals of *Giardia* cysts exceed 95 percent. Similar relationships exist for the other parameters investigated. There was a lower confidence level, however, using particle counting as a surrogate indicator.

Turbidity was found to be a good indicator of percent removals of other parameters as well, e.g. standard plate count bacteria, and total coliform bacteria. High removals of turbidity, e.g. from 0.5 NTU to 0.1 NTU, are evidence that filtration has occurred with effective coagulation. If effective coagulation-filtration occurs, then very high removals can be expected for all substances, e.g. bacteria, cysts, etc.

Field-scale results showed that percent removals of turbidity were associated with percent removals of Giardia cysts and coliform bacteria. These associations were established in testing using waters from both Horsetooth Reservoir and the Cache La Poudre River. Also associations were established between percent removals of coliform bacteria and percent removals of Giardia cysts. These associations indicate that coagulants effective in reducing turbidity by more than 80 percent will remove coliform bacteria and Giardia cysts at the 90 to 98 percent level, corroborating findings at the lab-scale.

Percent removal of total coliform bacteria would be an excellent indicator of filtration efficiency. In low turbidity water situations, however, the ambient water concentrations of total coliform bacteria are very low, e.g. 0-100 org/100 mL. Because suitable measures of filtration effectiveness may be lacking when dealing with low turbidity waters, the use of a lab-scale pilot plant, operated adjacent to the full scale plant, is strongly recommended. The raw water for the pilot plant could be spiked with a source of coliform bacteria as a means to evaluate existing or contemplated treatment.

SECTION 3

METHODS

RESEARCH PLAN

The research plan was based upon utilization of two physical models of the rapid rate filtration process. One was a 1.32 L/min flow capacity laboratory-scale rapid rate filtration pilot plant, constructed for this research. The other was a 76 L/min flow capacity trailer mounted WATER BOY® field-scale rapid rate filtration pilot plant. The pilot plants were used to ascertain the effect of selected independent variables on a group of dependent variables. The dependent variable of major interest was the removal of Giardia lamblia cysts. Others included removals of turbidity, standard plate count bacteria, total coliform bacteria, and particles. The independent variables, which are "process" variables, are the coagulants used, dosages of coagulants, coagulant sequence, mode of filtration, filter media, filtration rate, temperature, and run time. Thus the research plan was to conduct experiments varying the magnitude or a characteristic of each independent variable systematically while holding the others constant, and at the same time, measuring the responses of the dependent variables. The laboratory-scale pilot plant was used to test the effects of many process variables over a wide range. The field-scale pilot plant was used to confirm findings obtained using the laboratory-scale pilot plant. The range of testing was more limited and was done under ambient conditions.

In this section the overall research plan is described. It includes: a description of the testing space, an outline of the experimental design, and a review of the work plan.

Testing Space

Figure 2 illustrates the concept of the experimental "testing space." The dependent variables, Giardia cysts, turbidity, particles, total coliform bacteria, and standard plate count bacteria, are indicated by the heavy vertical arrow. They "respond" to the independent variables categorized as water characteristics, chemical basin conditions, and filter condition. Within the categories the independent variables, i.e. process variables are identified. Twelve such variables are shown in this conceptual depiction. Conceptually each arrow represents a possible range of testing for the respective variable depicted. The temperature arrow for example indicates the range of the testing space for these experiments, e.g. $0^{o}C$ to $20^{o}C$. It shows "tic marks" at temperatures where tests might be performed. The

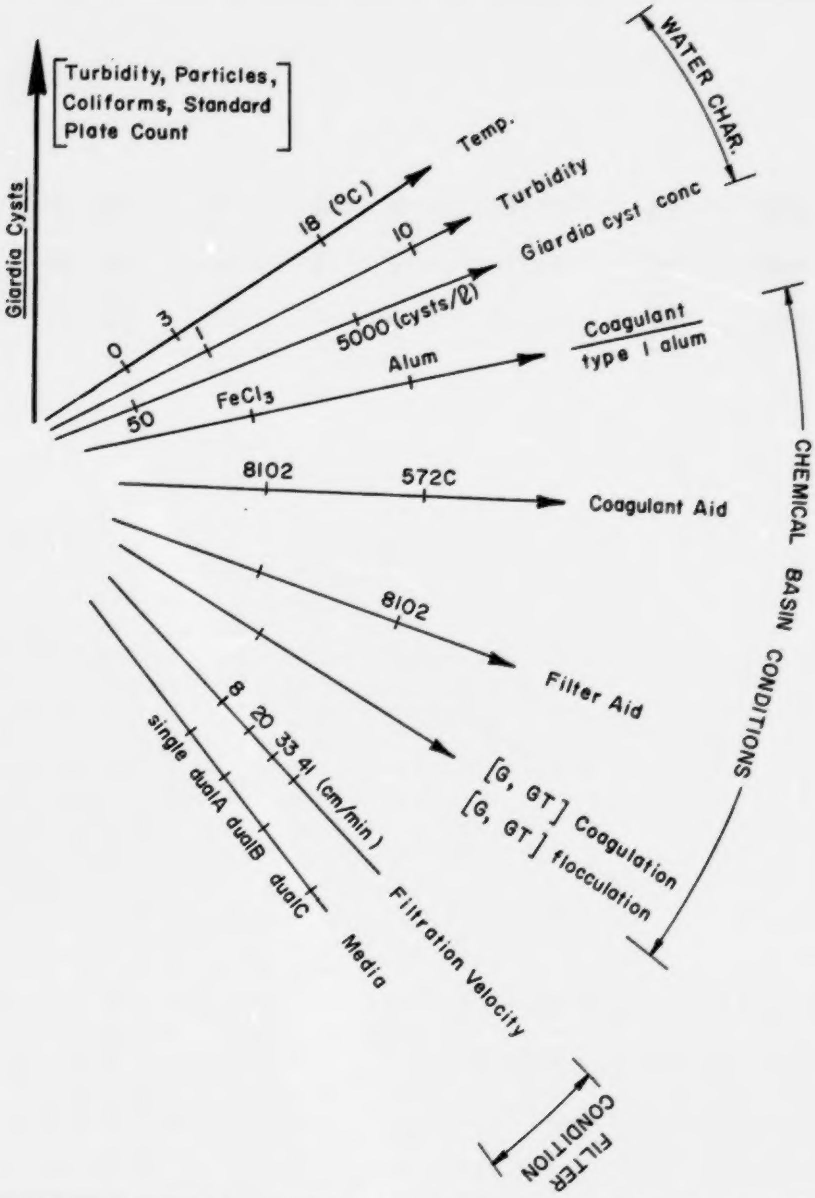

Turbidity, Particles, Coliforms, Standard Plate Count
Giardia Cysts
Temp.
0
3
18 (°C)
Turbidity
1
10
Giardia cyst conc
5000 (cysts/ℓ)
50
FeCl$_3$
Alum
Coagulant
type I alum
8102
572C
Coagulant Aid
8102
Filter Aid
[G, GT] Coagulation
[G, GT] flocculation
8
20
33
41 (cm/min)
Filtration Velocity
single
dualA
dualB
dualC
Media
WATER CHAR.
CHEMICAL BASIN CONDITIONS
FILTER CONDITION

Figure 2. Experimental testing space illustrating the range of experimental work.

turbidity arrow shows tic marks at 1 NTU and at 10 NTU. This was the turbidity domain where all testing was conducted. But the focus of the experimentation was on waters having raw water turbidities of less than 1 NTU.

Figure 2 is an approximation of the actual testing space in which experiments were conducted for the laboratory-scale pilot plant. For the field-scale pilot plant the range of testing was more limited. The knowledge gained during the laboratory-scale experiments was used as the starting point in conducting the field-scale verifications. The main point is that within the range possible for each variable, tests were conducted only at selected points; otherwise the amount of testing would be prohibitive.

Experimental Design

Figure 3 is a three-dimensional matrix showing a portion of the experimental testing space for the laboratory-scale work. It illustrates a design for systematically conducting a sequence of experiments to evaluate the effect of process variables on removal of Giardia cysts by rapid rate filtration. The matrix shows the sequence of testing by starting the experiments at the easiest condition for removal of Giardia cysts, deemed to occur at point 1, where coagulation should be easiest. If substantial Giardia cyst breakthrough occurs under such conditions, then one would conclude that rapid rate filtration is not effective under any conditions. Then we terminate experiment, "TE". If no substantial breakthrough occurs, "NB", then more severe conditions will be imposed in the sequence indicated. Finally, if we end up at point 8 (i.e. $5^{o}C$, <1 NTU, 33 cm/min), and no breakthrough occurs, we can conclude the rapid rate filtration is highly effective under the most severe conditions. If any of the tests are terminated, indicated as "TE," then different coagulants will be tried and the sequence will be repeated. While this diagram is for illustrative purposes only, it shows conceptually the approach toward the research.

Plan of Experimentation - Laboratory-Scale Pilot Plant

The first task in the experimental program was to screen polymers for use as coagulant aids. Several hundred polymers are on the market. This was done using a "jar-filter" test technique, reported by Choi (1983) and by Brink (1984). Nine polymers were obtained as samples from manufacturers and were tested in conjunction with alum as the primary coagulant. Turbidity removal was the measure of effectiveness used. Two polymers, Magnifloc 572C® and Magnifloc 573C® were selected for conducting most of the experimental work using low turbidity water.

The next step involved comparing single media of sand with dual media of anthracite and sand. Since the rate of headloss increase was higher with single media, further testing was done exclusivey with dual media.

Also in the initial period two modes of rapid rate filtration were compared, e.g. "in-line," which is rapid mix followed by filtration, and "direct," which is rapid mix, flocculation, and filtration. Since results

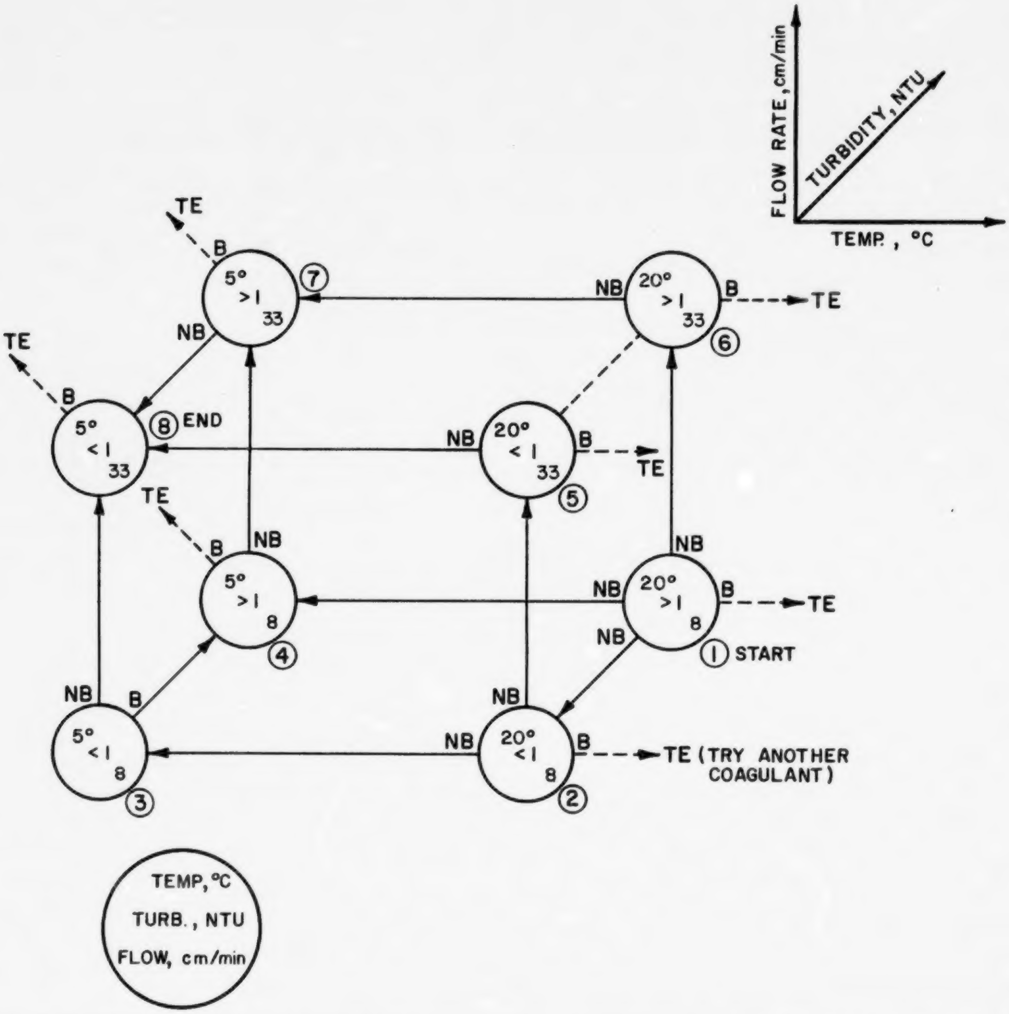

FLOW RATE, cm/min
TURBIDITY, NTU
TEMP., °C
TE
B
5°
>1
33
⑦
NB
20°
>1
33
B
TE
⑥
TE
B
5°
<1
33
⑧ END
NB
20°
<1
33
B
TE
⑤
TE
B
NB
5°
>1
8
④
NB
20°
>1
8
B
TE
NB
① START
NB
B
5°
<1
8
③
NB
NB
20°
<1
8
B
TE (TRY ANOTHER COAGULANT)
②
TEMP, °C
TURB., NTU
FLOW, cm/min

Figure 3. Matrix of testing space illustrating conceptually a possible sequence of experiments using the laboratory-scale rapid rate filtration pilot plant.

were the same all further work was done using "in-line" filtration.

In addition, for the purpose of learning the behavior of the system and to develop experience, raw water from Horsetooth Reservoir was used in initial exploratory testing. This water is more easily treatable as compared with low turbidity water. The data obtained are indicated in Table A-1, but they were not a main focus of this research.

After these preliminary results were obtained, the research could focus on fewer variables, such as filtration velocity, temperature, etc. Table 3

Table 3. Process variables and their operating conditions during rapid rate filtration experiments for Giardia cyst removal.

Process Variable	Operating Conditions
Raw water	(1) Horsetooth Reservoir water treated with diatomaceous earth to reduce turbidity to less than 1 NTU. (2) Cache La Poudre River water, winter condition at <1 NTU.
Temperature	3^{o}C and 18^{o}C
Coagulants	Alum Polymers Magnifloc 572C Magnifloc 573C Nalco 8102
Coagulant sequence	Alum added first then polymer Polymer added first then alum Alum and polymer in same mixing basin
Filter media	Single media: 76 cm bed sand D_{10} = 0.43 UC = 1.5 Dual Media: 30 cm sand bed D_{10} = 0.43 UC = 1.5 45 cm anthracite D_{10} = 0.9 UC = 1.5 Dual Media: 30 cm sand bed D_{10} = 0.5 UC = 1.4 45 cm anthracite D_{10} = 0.9 UC = 1.5
Hydraulic loading rate	2,5,8 gpm/ft^{2} (8.24, 22.5, 32 cm/min)
Pretreatment process	"In-line" mode, one or two stage of rapid mix with 180-290 sec detention time, and G = 40-300 sec^{-1} each stage

describes the process variables used in the experimental program and describes the operating range for each.

The dependent variables measured are listed in Table 4. They were chosen in order to provide a full complement of variables which possibly could serve as indicators of filtration performance. The same set of dependent variables were measured during both laboratory-scale and field-scale testing, except particles were not counted for the latter work.

Table 4. Dependent variables measured in testing rapid rate filtration performance.

1. Turbidity
2. _Giardia_ _lamblia_ cysts
3. Total coliform bacteria
4. Standard plate count bacteria
5. Particle counts

Plan of Experimentation - Field-Scale Pilot Plant

The overall research plan used for the field-scale experimentation is enumerated below.

i) Select coagulants based upon bench-scale and laboratory-scale pilot plant results.

ii) Establish fixed conditions for conducting the field-scale testing (e.g. filtration mode, hydraulic loading rate, etc.), based upon results of laboratory-scale pilot plant testing.

iii) Develop effluent turbidity vs coagulant dose curves for each coagulant selected in step i).

iv) Determine removals of _Giardia_ cysts and coliform bacteria for each coagulant at "optimum" and "nonoptimum" dosages with respect to turbidity removal, and also for "zero" dosage of coagulants.

v) Establish the headloss and effluent turbidity vs time relations for the effective coagulants at "optimum" dosage.

vi) Execute steps i) to v) for Horsetooth Reservoir water and for low-turbidity Cache La Poudre River water.

The above plan encompassed two categories of testing: i) effluent turbidity vs coagulant dose; and ii) _Giardia_ cyst and coliform bacteria removals vs coagulant dose. The effluent turbidity vs coagulant dose tests were to establish relationships between finished water turbidity and coagulant dosage, for specified conditions (e.g. type of water, hydraulic loading rate, etc.). The purpose was to determine the "optimum" coagulant dosage range for the field-scale pilot plant, as defined by turbidity removal. The effluent turbidity after one-hour of operation was taken as the "stabilized" turbidity. No Giardia cysts or coliform bacteria were injected during these tests.

Once the relationship between effluent turbidity and coagulant dosage was established, tests were performed to determine removals of Giardia cysts and coliform bacteria at "optimum" and "nonoptimum" chemical dosages, and at "zero" dosages. The "zero" dosage tests were to establish a "baseline" to compare Giardia cyst and coliform bacteria removals with the same tests using coagulant chemicals.

The Giardia cyst and coliform bacteria removals vs coagulant dose testing protocol consisted of: i) backwashing; ii) starting the raw water pump, the chemical feed pumps, and the contaminant injection pump; iii) waiting for one-hour for the system to stabilize; iv) sample influent and effluent for Giardia cysts and coliform bacteria concentrations.

PILOT PLANT - LABORATORY-SCALE

The laboratory-scale rapid rate filtration pilot plant was the physical model used to conduct the experimental work over a broad range of process variables. Figure 4 is a schematic drawing of the pilot plant showing each of the components comprising it, e.g. chemical feed, rapid mix, flocculation, sedimentation, and filtration. Figure 5 is a photograph showing the overall layout. After the rapid mix, the pilot plant is dual train. It was set up to operate in "in-line," "direct," or "conventional" filtration modes. It was designed to permit maximum flexibility in chemical pretreatment, and in controlling process variables such as temperature and filtration velocity. Descriptions follow of the pilot plant components and their respective operations.

Description of Laboratory-Scale Pilot Plant

The pilot plant, shown in Figures 4 and 5, was designed for dual train operation to permit concurrent testing with two different independent variables. All components were designed for pressure operation because of limited height available for the filters. It has four filter columns, e.g. two of 5 cm diameter and two of 10 cm diameter. The maximum pumping capacity was 1.32 L/min. At this flow the pilot plant, with one of the 5 cm filters, could be operated for 16 hours duration with one filling of the 1400 liter milk cooler used to store the raw water supply. The maximum filtration velocity possible is 65 cm/min (16 gpm/ft^2) if one of the 5 cm filters is operated alone with the maximum flow of 1.32 liters/min. Appendix C shows the design computations and shop drawings for each unit process.

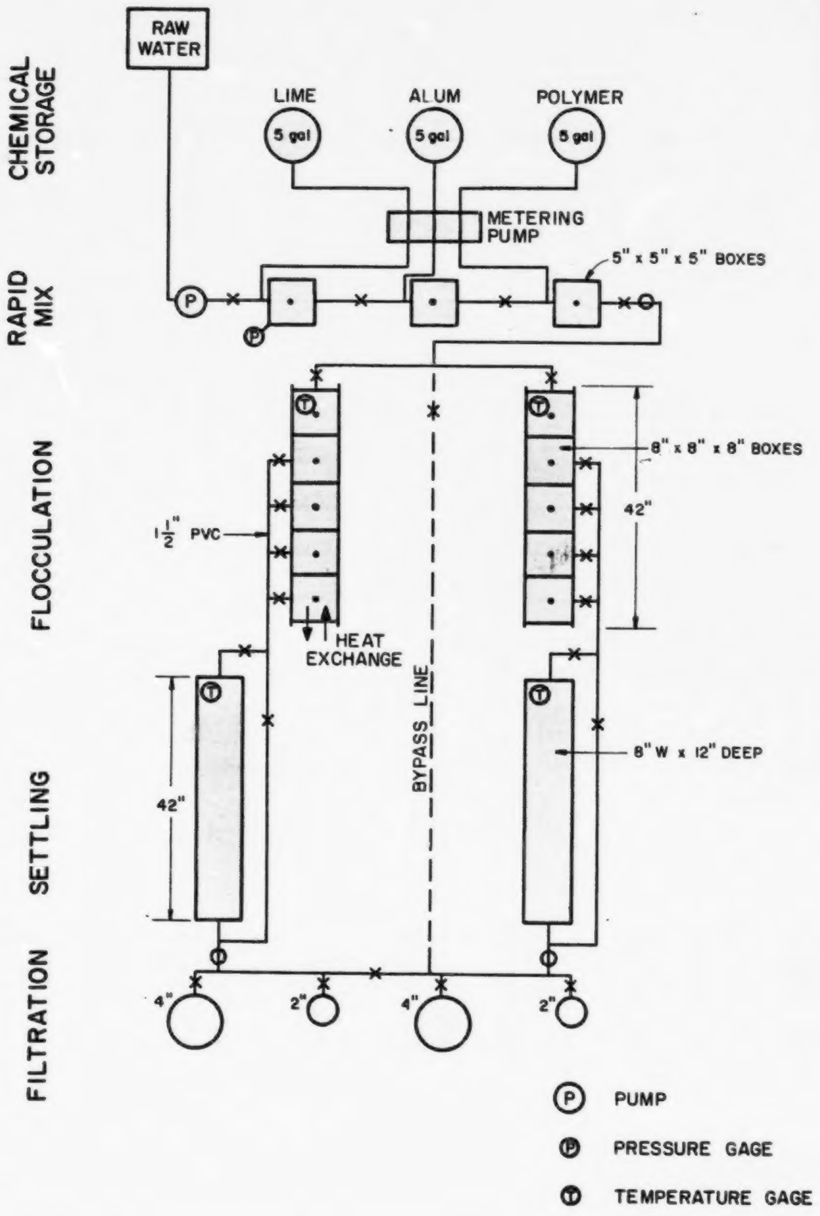

CHEMICAL STORAGE
RAPID MIX
FLOCCULATION
SETTLING
FILTRATION
RAW WATER
LIME
5 gal
ALUM
5 gal
POLYMER
5 gal
METERING PUMP
5" x 5" x 5" BOXES
P
P
T
T
8" x 8" x 8" BOXES
42"
1 1/2" PVC
HEAT EXCHANGE
BYPASS LINE
T
T
8" W x 12" DEEP
42"
4"
2"
4"
2"
P PUMP
P PRESSURE GAGE
T TEMPERATURE GAGE

Figure 4. Schematic drawing of laboratory-scale rapid rate filtration pilot plant.

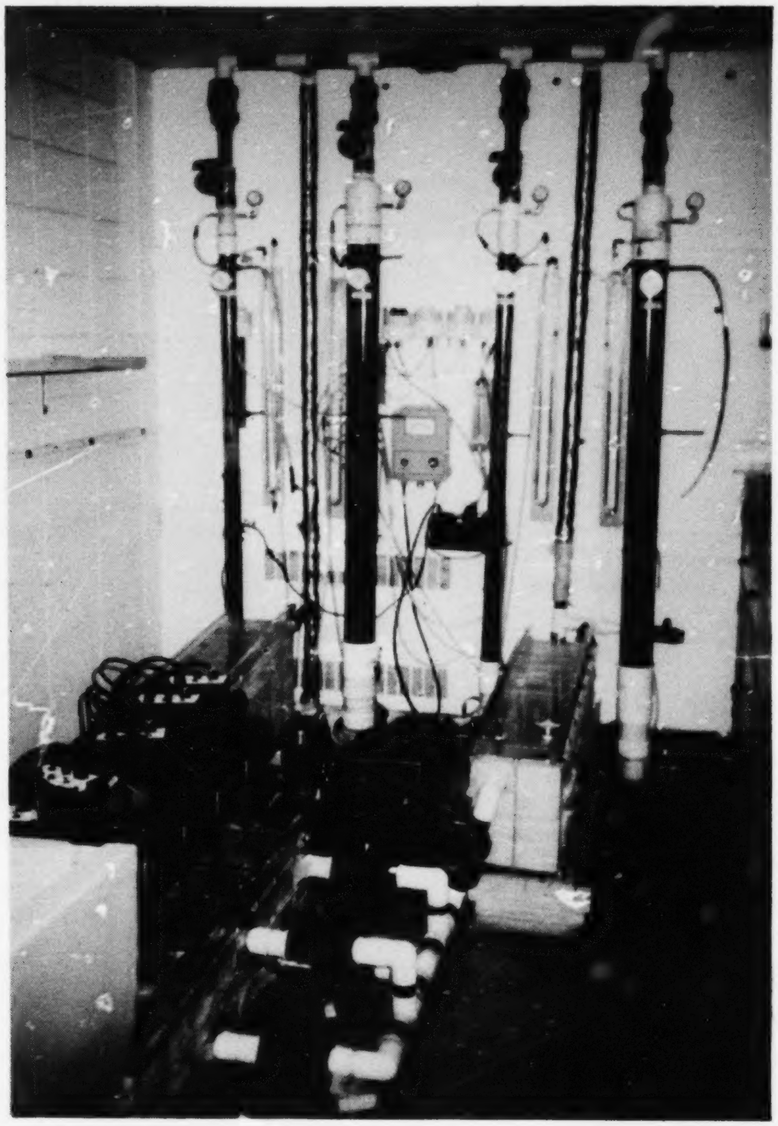


Figure 5. Photograph of laboratory-scale rate filtration pilot plant.

Water Storage--

A 1400 liter milk cooler was used for storage and temperature control of the raw water. Figure 6 is a photograph. For a filtration run, Giardia cysts and total coliform bacteria were added to the milk cooler in known concentrations.

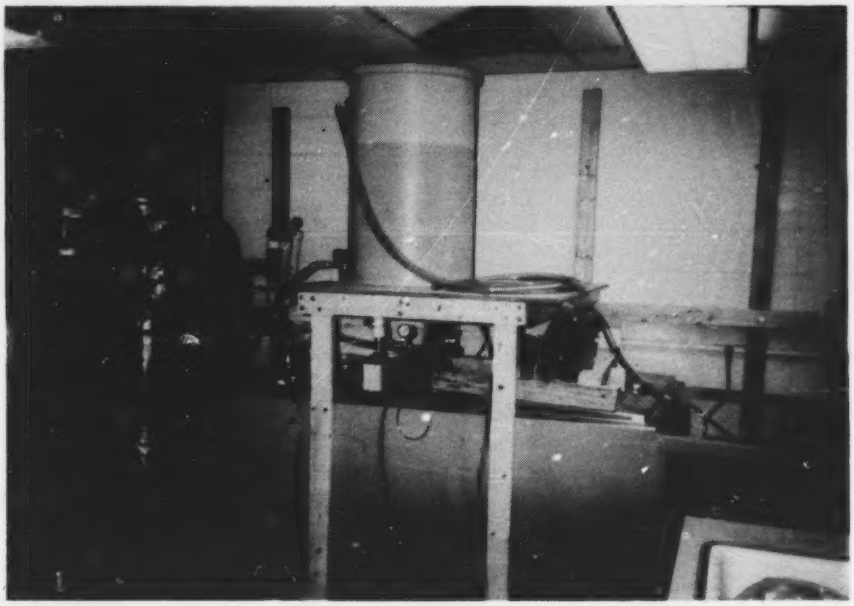


Figure 6. Milk cooler for storage and temperature control of raw water supply for laboratory-scale rapid rate filtration pilot plant.

Pump--

The pilot plant was operated under pressure using a Fluid Metering Model FMI piston pump, having flow capacity of 1.32 L/min. To control pressure fluctuations, a pressure damper was located after the pump. A pressure gauge was located at the top of the damper. Pressure fluctuations were not detectable.

Rapid Mix--

Three rapid mix boxes were located in series after the pump-damper unit. Figure 7 shows the units. These boxes are each 12.7 cm x 12.7 cm x 12.7 cm inside dimensions. Each stirring paddle has four rectangular blades 1.25 cm x 1.25 cm each, mounted on the stirring shaft. Appendix C gives complete design detail. The paddle speeds are controlled by variable speed motors. Chemicals may be added in sequence, one to each box from three storage tanks.

The piping from the pump to the rapid mix basins was modified from that shown in Figure 4 to permit flow directly to the second basin or to the third basin, as well as to the first basin. Also the flow from the third basin

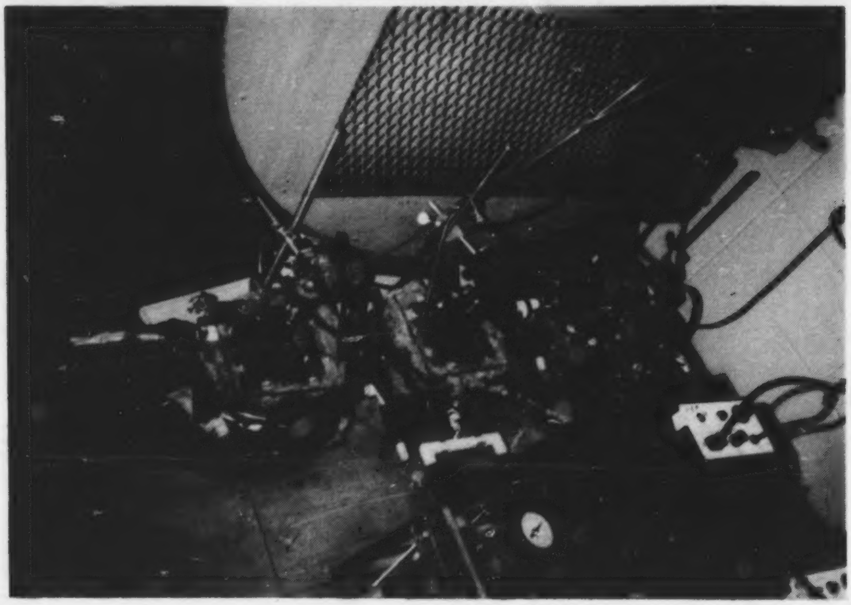


Figure 7. Rapid mix units, laboratory-scale rapid rate filtration pilot plant.

could enter either or both of the flocculation basins, or bypass these, using 2.54 cm inside diameter flexible tubing, to enter the filters.

Chemical Storage--

Figure 8 shows three 20 liter plastic tanks used for chemical storage. The chemicals were mixed and flows were controlled by a multichannel metering pump. The chemicals set-up was for lime, alum, and polymer, which was the designed feed sequence to the rapid mix basins. The concentrations of the chemicals in storage were matched to the low limit capacity of the metering pump, which was 0.2 mL/min, and the chemical dosage required. The maximum flow of a metering pump channel was 20 mL/min.

Flocculation Basins--

Figure 9 shows one of the two floccuation basins. The flow from the rapid mix may be split into the two basins. Each basin has five compartments, 20.3 cm x 20.3 cm x 20.3 cm dimensions. The basin can be operated using two, three, four or five compartments by means of valves on the pipe manifold.

Each compartment contains a flocculation paddle having four verticle blades 0.95 cm wide and 14.6 cm long, spaced 3.17 cm and 5.71 cm from the shaft. The paddles are driven by individual variable speed motors, controlled by rheostats, also shown in Figure 9.

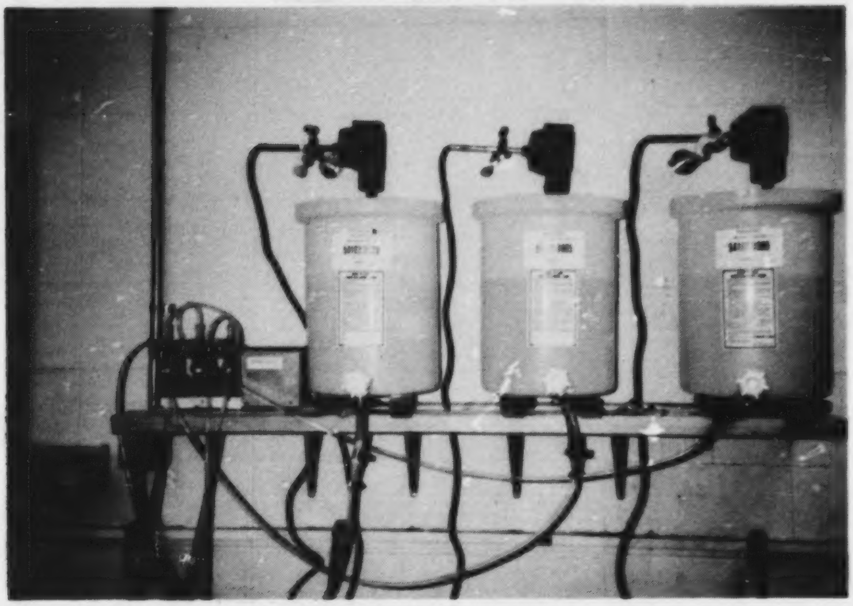


Figure 8. Chemical feed tanks and metering pumps, laboratory-scale rapid rate filtration pilot plant.

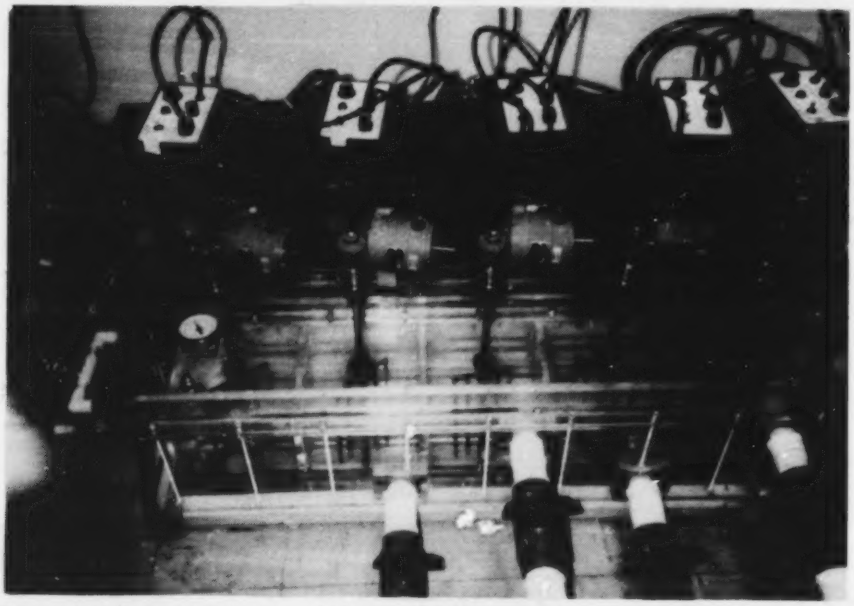


Figure 9. Flocculation basins with paddles, motors, and rheostats for laboratory-scale rapid rate filtration pilot plant.

The water temperature in the flocculation compartments could be controlled by 0.64 cm diameter copper tubes used as heat exchange elements. The coolant can be circulated from an external heat exchanger, capable of refrigeration or heating. Testing established that the heat exchange system can maintain freezing temperature in the flocculation basin in the refrigeration mode.

The manifold pipes from the basins are 3.8 cm dia. This large size was selected both to have sufficient velocity to maintain the floc in suspension, and to avoid floc breakup by turbulence. The pipes used were clear PVC plastic to permit observation of floc movement. This pipe system leads to the sedimentation tank but permits bypass to the filters.

Sedimentation Basin--

The sedimentation basin was designed to handle a wide range of detention times and overflow velocities. The former can range from 1 to 1.7 hr for the highest flows. Figure 10 is a photograph of the tank. The tank is 20.3 cm wide and 33.0 cm in depth at the head and 30.5 cm in depth at the end. The length is variable from 52 cm to 100 cm, through the use of partitions. If a short tank length is used the distance between the partitions can be connected by short pipe lengths. An air drain valve is located on the top surface of the basin. A copper tube heat exchange element is located inside for temperature control, which can be seen in Figure 10. The tank also has an inclined floor toward the head with a floor drain to remove settled floc and drain the basin.

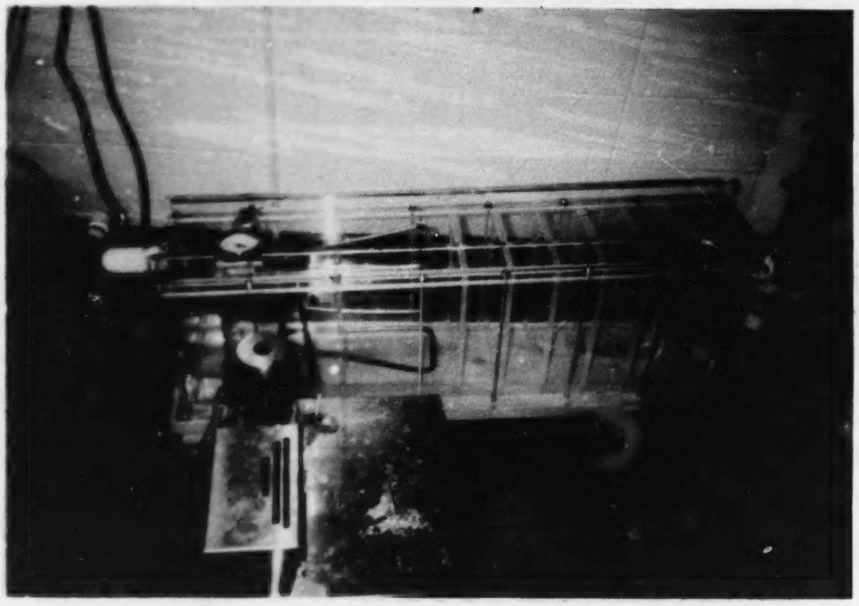


Figure 10. Sedimentation tank, for laboratory-scale rapid rate filtration pilot plant.

Filters--

Figure 4 shows the general layout of the four filters in relation to the other components. The photograph Figure 5 also shows the four filters in relation to the other components of the pilot plant. The filters, in sequence from left to right designated by inside diameters and media used in initial experiments, are: 5.0 cm sand, 10 cm dual media, 5.0 cm dual media, and 10 cm sand. Additional information on media was given in Table 3.

The manifold system to the filters permits operation of any combination of filters with either of the two flocculation-sedimentation trains. The system can be operated also from rapid-mix coagulation to filtration, i.e. "in-line" filtration.

The sieve analysis for the sand used is shown in Figure 11. The effective diameter was 0.43 mm, and uniformity coefficient was 1.50, which are common specifications in practice. The seive analysis for the anthracite is shown in Figure 12. The effective diameter was 0.9 mm and the uniformity coefficient was 1.5, which also conforms with practice.

Figure 13 shows a close-up for one of the 10 cm filter columns. The system was set up for air scrubbing conducted prior to or during to backwash. This also alleviates the problem of the entire media lifting at once during backwash. Headloss across the media in each column was measured by a mercury manometer. Tap connections were located at different distances along the length of the column. These permitted both sampling and pressure measurements between any two points. Temperature and pressure gauges were located at the top of the column.

The flow from any column could be directed through a 1.2 cm diameter pipe for Giardia cyst sampling as shown in Figure 14. Constant head overflow weir devices were located for tail water control, maintained above the media, which insured that negative pressures within the filters were avoided.

Operation

Sources of Water--

When turbidity levels in the Cache La Poudre River were 1 NTU or less then water was transported from the river by two trailer mounted 1000 liter tanks, shown in Figure 15. This water was then pumped to the milk cooler for use. The water was obtaind from the river at the site of Fort Collins Water Treatment Plant No. 1.

Flow--

The pilot plant flows were regulated by a positive displacement pump (FLUID Metering Model FMI ®) having flow range between 0 and 1.3 liters/min. The flow was controlled by changing stroke length of the piston, which was calibrated on a dial. This was used to set the flow; measurement was made volumetrically.

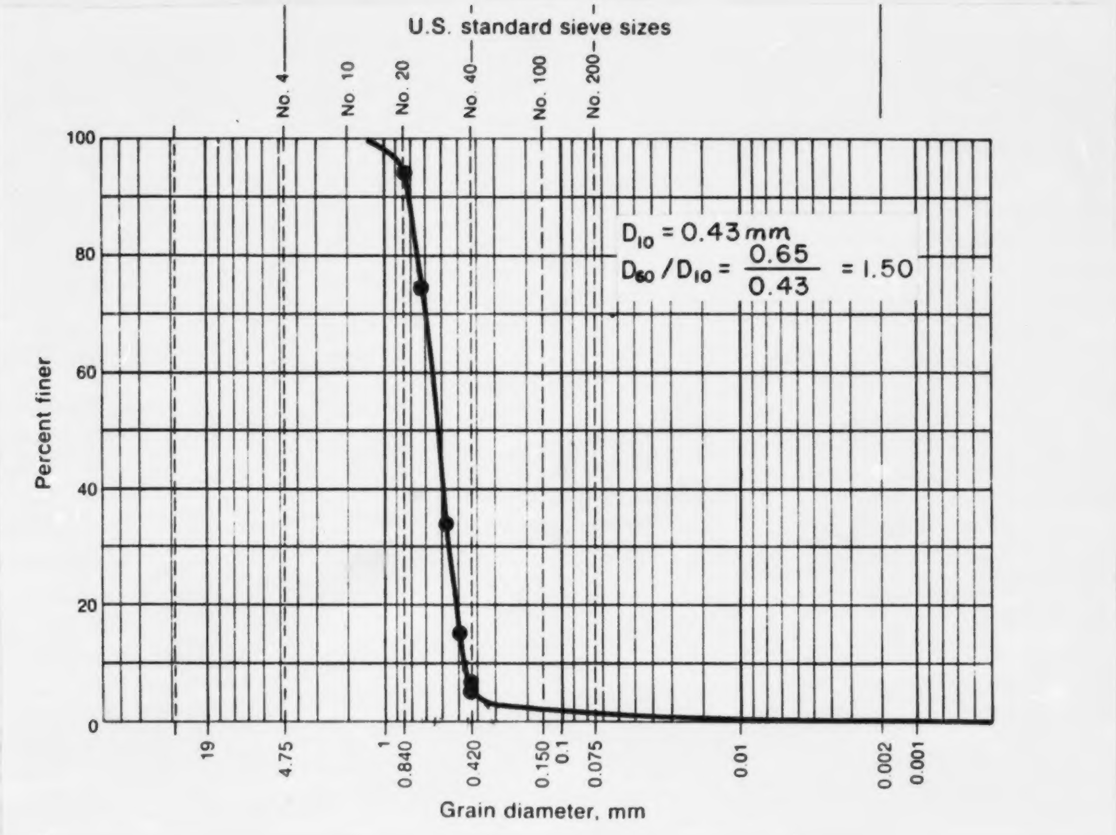


Figure 11. Sieve analysis for filter sand, used in sand filter and sand portion of dual media filter, laboratory-scale rapid rate filtration pilot plant. Source of sand was Loveland treatment plant at Big Thompson Canyon.

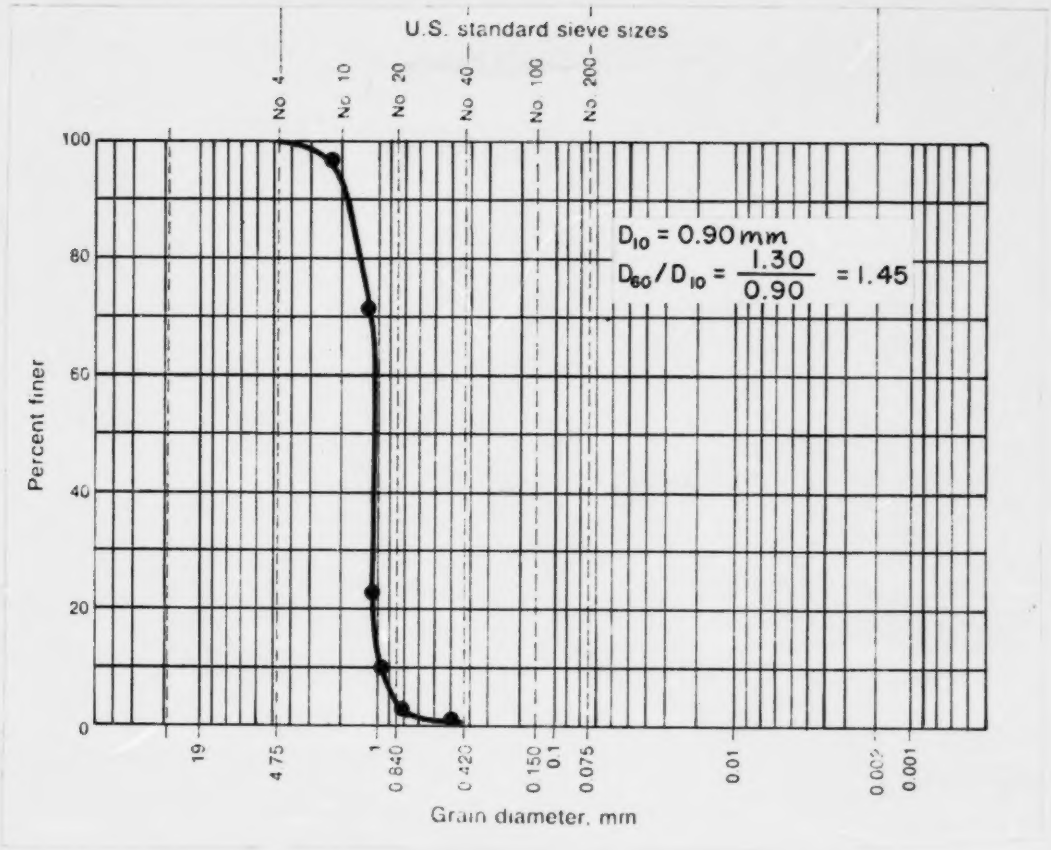


Figure 12. Sieve analysis for anthracite used in dual media filter, laboratory-scale rapid rate filtration pilot plant. Anthracite has brand name Philterkol Special No. 1.

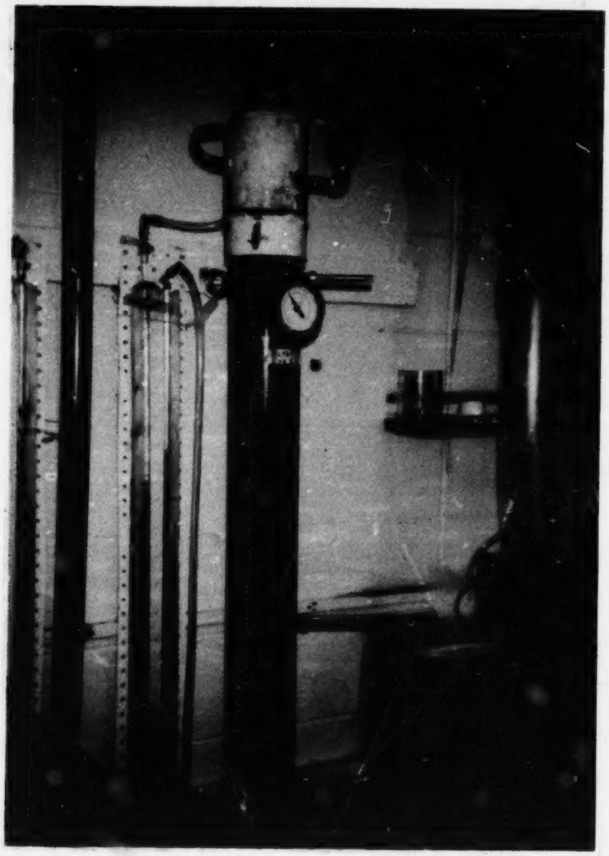


Figure 13. Close-up of 10 cm diameter filter column, laboratory-scale rapid rate filtration pilot plant.

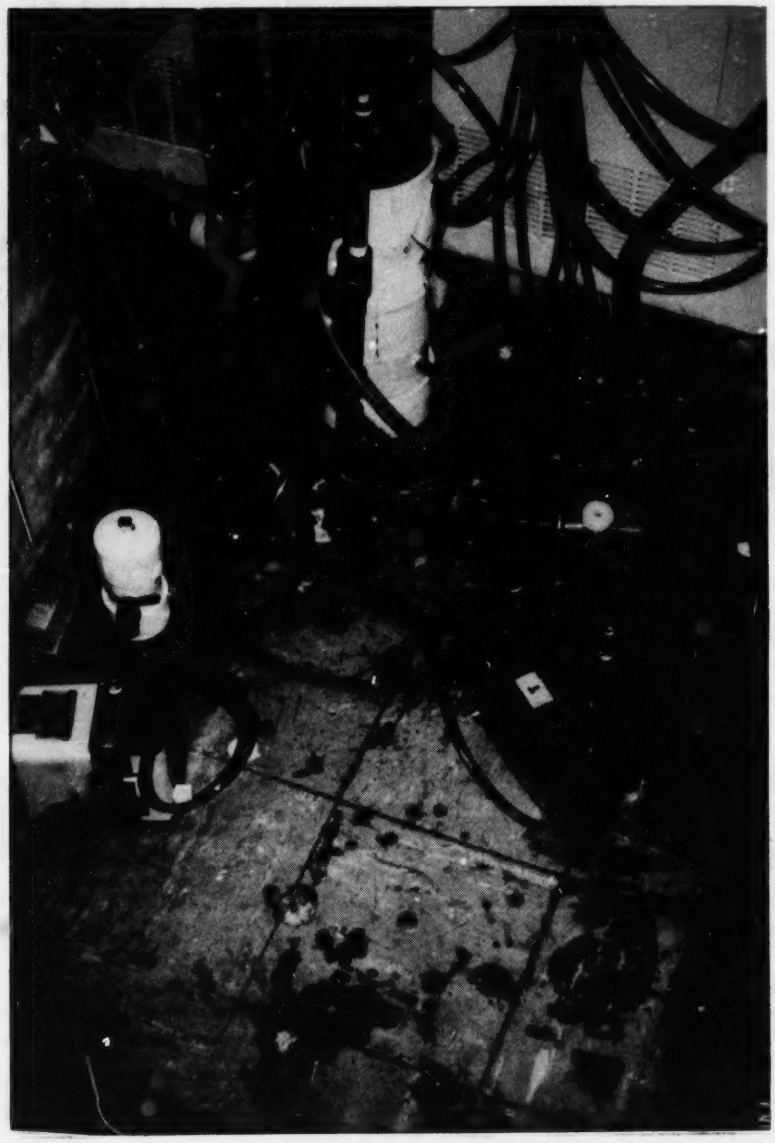


Figure 14. Membrane filter, 142 mm diameter, set up for Giardia cyst sampling of filter effluent, laboratory-scale rapid rate filtration pilot plant.

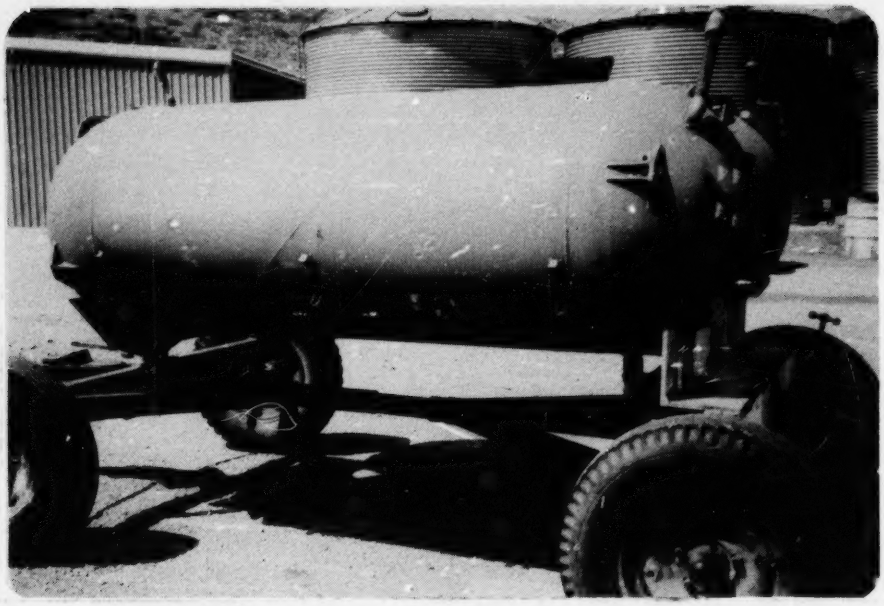


Figure 15. **Tanks mounted on trailer for hauling water from Cache La Poudre River for laboratory-scale rapid rate filtration pilot plant. Tank capacity is 1000 liters each cylinder. Lining is stainless steel.**

Rapid Mix--

As noted, the three rapid mix basins could be operated three or two in sequence, or using only one basin. The mixing intensity, as measured by velocity gradient G, could be controlled by varying the motor speed for the mixer, using a rheostat SCR Cole Parmer Model 4555-30®. The motor was a COLE-PARMER Model C-4555®, and had two shafts for different speed ranges. The higher speed shaft had an upper limit of rotational speed, in the coagulation box filled with water, of 720 rpm. Early in the experimentation rotational speeds used were only 150 rpm, with corresponding G of about 37 sec^{-1}. Later a speed of 600 rpm was used to give a G value of about 300 sec^{-1}. Appendix C shows the calculations of G for the paddle mixer design used. Figure C-7 shows the G vs paddle shaft rpm for 4°C and 20°C. Subsequent to Run 70, G values were maintained in the range 200 sec^{-1} to 300 sec^{-1}.

Chemical Feed--

Chemical feed rates were set and maintained by a Cole-Parmer Model C-7091 R multichannel positive displacement "bellows" pump. Flows were set by using graduations for each channels used, and were measured volumetrically for 10 minutes duration. The range of flows possible was 0 to 20 mL/min for each channel. The flows used depended upon the concentration of the stock solution and the dosage required. Flows of stock solution were calculated by materials balance, e.g.

$$\text{Flow in pilot plant} \times \text{chem. conc. desired} = \text{Flow from stock sol.} \times \text{chem. conc. in stock sol.}$$

To illustrate, if the pilot plant flow is 450 mL/min, the polymer concentration desired is 3.0 mg/L, and the polymer concentration in the stock solution is 1 gm/L, then the stock solution flow must be 1.35 mL/min. These flows were checked volumetrically about once each hour.

The stock solutions were made up daily. The polymer stock solution, using liquid polymer, was made up by pipetting 1.0 mL of polymer, presumed to have density of 1.0 gm/mL, to 1000 mL of distilled water. The liquid polymer was presumed for measuring purposes to be pure polymer, albeit the polymer solutions as provided by the manufacturers have unspecified concentrations of both salt and water. The alum stock solution was made up using liquid alum, in which 10 mL of liquid alum, containing 6430 mg $Al_2(SO_4)_3.14H_2O$, was added to 990 mL of distilled water. Appendix I shows the calculations involving liquid alum, based upon manufacturers data.

Flocculation—

The flocculation basin was operated only for the first two test runs. Later, comparisons were made between "in-line" and "direct" filtration which documented that the effluent turidities were the same when using low turbidity waters. In preliminary testing it was established that the flocculation basin temperature could be maintained at about 3°c.

Sedimentation—

The sedimentation basins were not used. Settleable floc was not observed in any of the tests with low turbidity water.

Filtration—

In preliminary testing two filters were run simultaneously. With such operation, however, it was not possible to obtain all of the necessary readings due to the labor requirement. Therefore, only one filter was operated during subsequent test runs. The major concern was to maintain a selected filtration rate. This was done by volumetric measurements, every two hours. Temperature was maintained constant by copper coils in the head of the filter, using a Neslab Model RTE-4® circulating heat exchanger. The lowest temperature used was 3°C, since ice formation was a problem with lower temperatures. Pressure measurements were obtained in the head of the filter using a pressure gage. Headloss was measured by a mercury manometer.

Backwash was done at the termination of a test run. It was preceded by about 5 minutes of air scour, followed by 10 to 15 minutes of backwash in which the air scour was continued.

Three media were used during the testing program: single media of Loveland sand (from the Loveland, Colorado treatment plant), dual media (with Philterkol No. 1 ® anthracite and Loveland sand), and dual media (with Philterkol No. 1 ® anthracite and Fort Collins sand). The latter was used to be compatible with field-scale testing using the WATER BOY ® field-scale pilot plant.

Screening Chemicals--

Because of the large number of polymers available, and the thousands of dosage combinations, a bench-scale screening procedure was developed. This procedure was called the "jar-filtration" test, and is reported by Choi (1983) and by Brink (1984). The traditional jar test has no utility with low turbidity water, since flocs do not form. Therefore, it was decided to use the jar test as a simulated chemical pretreatment in conjunction with six small dual media filters, 5 cm diameter x 50 cm media depth. After rapid mix, the two liters of chemically pretreated water were poured through the filters, according to a procedure established. Effluent turbidities were measured and plotted as functions of chemical dosages. Typical U-shaped or L-shaped curves were always produced. Comparisons with the pilot plant results for the same conditions showed similar turbidity responses. Therefore, this procedure was used to screen polymers and to establish approximate dosages for the pilot plant testing. This procedure will be described in a forthcoming paper based upon the thesis works of Choi and Brink.

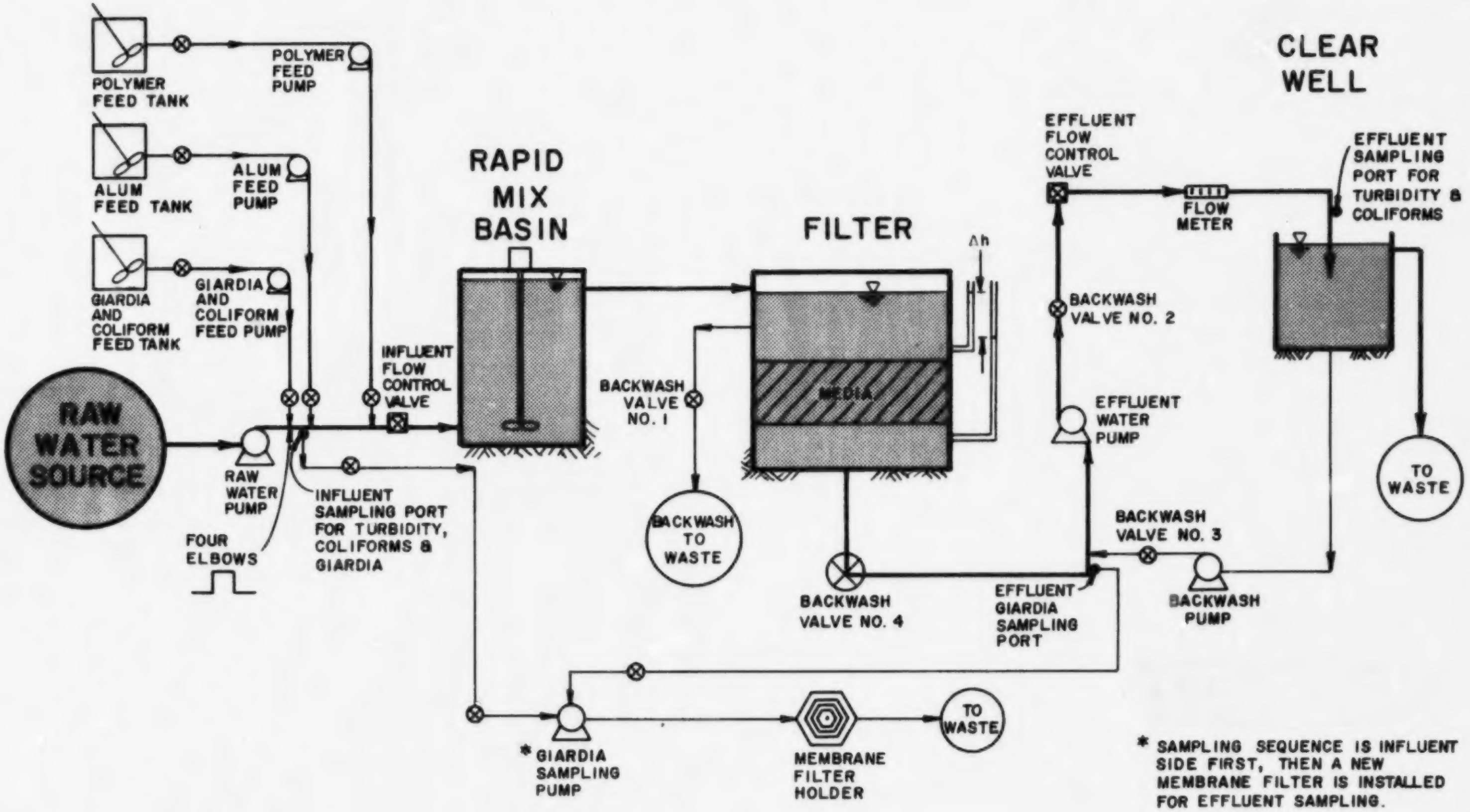
PILOT PLANT - FIELD-SCALE

A field-scale pilot plant was used to conduct further experiments under ambient raw water conditions. It was used to verify findings from the experimental work using the laboratory-scale pilot plant operated under controlled raw water conditions, such as using a uniform batch of water from a tank and with temperature control.

Description of Field-Scale Pilot Plant

Appendix D describes the field-scale pilot plant and its operation. Figure 16, which is the same as Figure D-6, is a schematic diagram of the WATER BOY rapid rate water filtration plant as modified for use in this research. Figure 16 shows the chemical feed system, the contaminant injection system, the sampling system, and the "in-line" filtration mode, which was used in this research. Figure 17 is a photograph of the WATER BOY. The WATER BOY is a Neptune Microfloc model WB-27 package water treatment plant. It was purchased by the U.S. Environmental Protection Agency Drinking Water Research Division in Cincinnati and mounted on a 22 foot trailer in order to have a mobile water treatment plant as a research tool. The plant was loaned to Colorado State University for this project.

Although nominally rated at 76 L/min (20 gpm), the WATER BOY has an upper limit water production capacity of 102 L/min (27 gpm), which is 16.6 m/hr (6.75 gpm/ft^2) hydraulic loading rate. At the production rate of 76 L/min (20 gpm), the plant can furnish water for 192 people based upon a per


POLYMER FEED TANK
POLYMER FEED PUMP
ALUM FEED TANK
ALUM FEED PUMP
GIARDIA AND COLIFORM FEED TANK
GIARDIA AND COLIFORM FEED PUMP
RAW WATER SOURCE
RAW WATER PUMP
FOUR ELBOWS
INFLUENT SAMPLING PORT FOR TURBIDITY, COLIFORMS & GIARDIA
INFLUENT FLOW CONTROL VALVE
RAPID MIX BASIN
BACKWASH VALVE NO. 1
BACKWASH TO WASTE
FILTER
MEDIA
Δh
BACKWASH VALVE NO. 4
EFFLUENT GIARDIA SAMPLING PORT
EFFLUENT FLOW CONTROL VALVE
BACKWASH VALVE NO. 2
EFFLUENT WATER PUMP
FLOW METER
CLEAR WELL
EFFLUENT SAMPLING PORT FOR TURBIDITY & COLIFORMS
TO WASTE
BACKWASH VALVE NO. 3
BACKWASH PUMP
* GIARDIA SAMPLING PUMP
MEMBRANE FILTER HOLDER
TO WASTE

* SAMPLING SEQUENCE IS INFLUENT SIDE FIRST, THEN A NEW MEMBRANE FILTER IS INSTALLED FOR EFFLUENT SAMPLING.

Figure 16. Schematic diagram of the WATER BOY pilot plant showing chemical feed, contaminant feed, and sampling system.

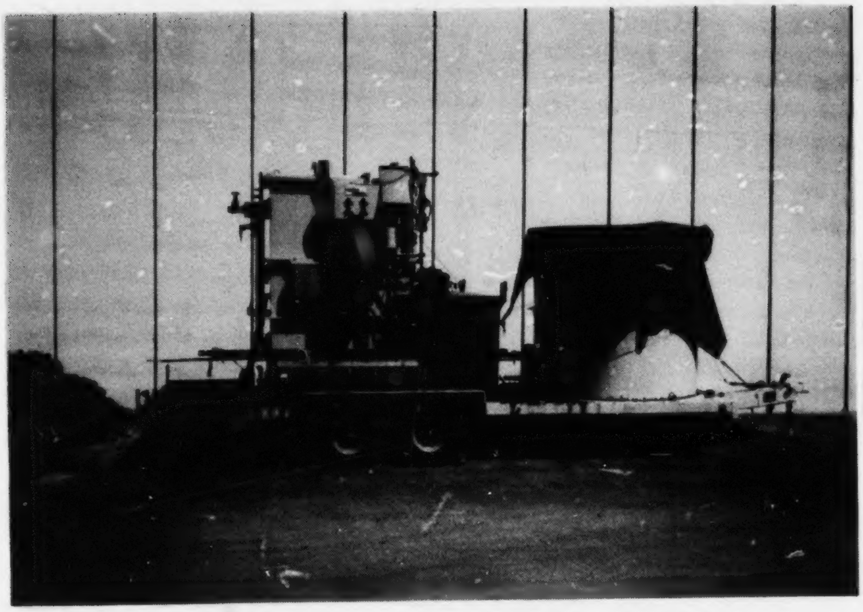


Figure 17. WATER BOY pilot plant on 22 foot trailer. The large cylindrical tank is the 4000 L clear well.

capita water consumption of 568 L/day/person (150 gpd/person). The plant is flexible in operation, permitting easy conversions between the three modes of filtration, i.e. "conventional" (rapid mix, flocculation, sedimentation, filtration), "direct" (rapid mix, flocculation, filtration), and "in-line" (rapid mix, filtration).

Appurtenances Utilized with Pilot Plant

Additional appurtenances were added to the pilot plant to provide for chemical feed, contaminant injection, and sampling. Figure 16 shows these appurtenances schematically, and Table 5 lists them. Special attention was given to in-pipe mixing of chemicals and contaminant injection. For example, the contaminants were injected into the middle of the pipe and four elbows were added to insure proper mixing prior to influent sampling at another point in the pipe. Similar precautions were taken to insure representative effluent samples. Appendix D describes the modifications for these purposes.

Test Conditions for Field-Scale Pilot Plant

Raw Water--

Three types of water were used in the field-scale pilot plant experimentation: i) Horsetooth Reservoir water, ii) Cache La Poudre River water during spring runoff, and iii) Cache La Poudre River water during late

Table 5. Appurtenances for Field-Scale Rapid Rate Filtration Pilot Plant[1/]

Item	Purpose & Specifications	Manufacturer	Model Designation
Raw Water Pump	Pumps Raw Water into Rapid Mix	Goulds Pumps, Inc.	XSH 15
Contaminant Feed Pump	Meters the contaminant batch into the main flow (0 to 1120 mL/min)	Fluid Metering, Inc	RP-D
Alum Feed Pump	Meters alum solution into main flow (0 to 75 mL/min)	Precision Control	111311-361
Polymer Feed Pump	Meters polymer solution into main flow (0 to 75 mL/min)	Precision Control	111311-361
Sodium Thiosulfate Feed Pump	Feeds $Na_2S_2O_3$ solution into effluent stream for dechlorination (50 to 1000 cc/min)	Cole Parmer	212
Giardia Sampling Pump	Diverts sampling stream from main flow through membrane filter (0 to 8.5 L/min)	Grainger	Rotary Beam Pump 1P771
Giardia Sampling Pump Motor	Drives *Giardia* sampling pump (3/4 hp)	Grainger	27846
Contaminant Batch Mixer	Agitates contaminant batch	Lightnin Mixers	Series 20
Alum Batch Mixer	Mixes alum solution	Wilkens-Anderson Co.	Power Stirrer
Polymer Batch Mixer	Mixes polymer solution	Cole Parmer	4555 H
Rapid Mix Basin Mixer	Disperses chemicals in rapid mix basin (1/4 hp) 1725 rpm	Lightnin Mixers	Mark II
Membrane Filter Holder	Holds 5 µm pore size 293 mm diameter membrane filters made by Nucleopore Corporation	Gelman Sciences	11873
Ratio Turbidimeter	Measures grab samples for turbidity	Hach Chemical Co.	18900-10
Flow-through Turbidimeter	Monitor influent and effluent turbidity	Hach Chemical Co.	1720-A

[1/] Neptune Microfloc Model WB-27 package water treatment plant rated at 76 L/min called WATER BOY®.

fall and winter when the raw water turbidity was less than 1 NTU. Table 6 shows the raw water characteristics of these waters. These characteristics are about the same from year to year.

Filtration Conditions—

All testing was conducted using "in-line" filtration with hydraulic loading rates between 9.7 and 12.6 m/hr (4 and 5.2 gpm/ft^2). Table 6 shows the ranges of filtration conditions which were tested.

Table 6.[1/] Raw Water Characteristics for Field-Scale Testing (average yearly ranges)

Characteristic	Horsetooth Water	Cache La Poudre During Spring Runoff	Cache La Poudre During Low Turbidity
Turbidity (NTU)	3 to 12	10 to 11	0.5 to 1.5
Temperature (C)	2 to 15	6 to 12	<1 to 7
pH	7.0 to 8.0	7.0 to 8.0	7.5 to 8.0
Alkalinity[2/]	10 to 50	30 to 40	35 to 45

[1/] Source: Summary of Chemical Analysis, 12 month averages, City of Fort Collins, 1981.

[2/] mg/L as $CaCO_3$.

Table 7. Filtration Conditions for Field-Scale Pilot Plant Testing

Condition	Range of Value Tested
Flow Rate, L/min (gpm)	60.1 to 83.3 (16 to 22)
Hydraulic Loading Rate, m/hr (gpm/ft^2)	9.7 to 12.6 (4 to 5.2)
Rapid Mix Detention Time, T sec (minutes)	145 to 250 (2.4 to 4.2)
Rapid Mix Velocity Gradient, G per sec	660 to 780
Rapid Mix GT	95000 to 200000
Turbidity of Water NTU	0.4 to 44
Temperature of Water °C	<1 to 13

Coagulants—

The selection of coagulants was based upon the results of the laboratory-scale pilot plant work. The chemicals selected, including the use of no chemicals i.e. "none", were used for a range of conditions to simulate what was anticipated would be both "good" and "poor" treatment. The chemicals used are enumerated as follows:

i) No Chemicals, i.e. filter used as strainer.

ii) Magnifloc 572-C as sole coagulant,

iii) Magnifloc 573-C as sole coagulant,

iv) Nalco 8102 as sole coagulant,

v) Alum as sole coagulant,

vi) Alum followed by Nalco 8102,

vii) Alum followed by Magnifloc 572-C.

Based upon the laboratory-scale pilot plant work, all but the last was anticipated to result in "poor" filtration results. This provided for an anticipated range of results to verify the laboratory-scale work.

MEASUREMENTS AND QUALITY CONTROL

The sampling and measurements taken routinely during test runs are described here with respect to methods, frequency, instruments used, and quality control. A quality control program was designed to assure that valid measurements were obtained and that equipment performed as intended. The paragraphs following describe these for both the laboratory-scale and field-scale pilot plant work. Procurement of cysts is discussed first.

Procurement of Giardia Cysts

Giardia cysts were obtained from dog feces at the Larimer County Humane Society, Fort Collins, Colorado. The fecal samples were taken to Dr. Hibler's laboratory at Colorado State University and checked for the presence of cysts. If cysts were present, then the sample was weighed and then added to an equal weight of cool, distilled water in a mason jar and stored at between 2 and 8°C until used. The cysts obtained were not used if over 10 days old. When used with the laboratory-scale pilot plant, this suspension of dog feces and distilled water, containing nominally about 5 million cysts, was placed into the milk cooler feed tank where it was mixed with raw water. When used with the field-scale pilot plant the suspension was mixed with water and raw primary sewage in 50 liter vessel from which the suspension was metered into the raw water stream.

Laboratory-Scale Measurements and Quality Control

Table 8 summarizes all measurements obtained using the laboratory scale rapid rae filtration pilot plant along with sampling methods, sampling points, sampling frequency, and quality control methods. All parameters used to measure filtration efficiency are listed. Table 9 summarizes routine measurements obtained to ascertain conditions of operation.

Cyst Sampling—

The only special comments required concerning Tables 8 and 9 relate to sampling and analysis of *Giardia* cyst samples. Sampling of the cyst suspension in the milk cooler was done by pumping a flow from the milk cooler tank through a 5 micrometer, 142 mm membrane filter and counting the

Table 8. Sampling and measurement of filtration efficiency parameters obtained in operation of laboratory-scale rapid rate filtration pilot plant.

Parameter Measured	Sampling Method	Sampling Points	Frequency of Sampling	Measurement Technique	Quality Control[3]
Turbidity	Grab, in cuvette	Milk cooler Filter effluent	Two hours Hourly	Turbidity meter Hach Model 1400	Standardized daily using 1.8 NTU standard
Particles	Grab, 300 mL bottle	Milk cooler Filter effluent	Daily Daily	Coulter counter Model TA II	Bottle washed with soap and rinsed with distilled water passed through 2 µ membrane filter. Coulter counter was standarized by use of standards having known particle numbers and sizes.
Standard plate count bacteria	Grab, using 250 mL sterile bottle	Milk cooler Filter effluent	Daily Daily	Plate count using tryptone glucose extract agar (DF0002-01-7)[1]	Duplicate plates and blank plate
Total coliform bacteria	Grab, using 250 mL sterile bottle	Milk cooler Filter effluent	Daily Daily	Plate count using Mendno MF agar[1]	Duplicate plates and blank plate
Giardia cysts	142 mm, 5 µm polycarbonate membrane filer sampling entire effluent[2]	Milk cooler Filter effluent	Daily Daily	Sample was washed from membrane filter, and analyzed by micropipette technique in lab of C. P. Hibler	1. Sampling. Filter holders were washed with hot, soapy water and rinsed. Collected samples were refrigerated. 2. Analysis. Standard lab protocol followed. 3. Cyst condition. A refrigerated cyst sample from the batch used in experiments was observed after test runs to ascertain cyst morphology.

[1] Microbiological Methods for Monitoring the Environment, EPA Publication 600/8-78-017, Cincinnati, 1978.

[2] Sampling was continued until pressure at top of filter column reached 5 psi; usually the sample volume was 20 to 40 liters.

[3] See Appendix H.

Table 9. Monitoring measurements and quality control in operation of laboratory scale rapid rate filtration pilot plant.

Parameter Measured	Measurement Method	Points of Measurement	Frequency	Instruments Used	Quality Control
Temperature	Perm. immersion	Milk cooler	Twice daily	Mercury therm.	NBS[2] thermometer
	Perm. mount in basin	Rapid mix basin	Hourly	Dial therm.	NBS therm.
	Perm. mount in col.	Filter column top	Hourly	Dial therm.	NBS therm.
	Temporary immersion	Filter tailwater cup	Hourly	Mercury therm.	NBS therm.
Flow	Volumetric	Filer effluent	Two hours	1000 mL grad. cyl. and stopwatch	Volumetric meas.
Chemical stocks					
1. Alum	no analysis	N.A.[1]	N.A.	N.A.	Liquid alum stock solution replaced after 2-3 months from F.C. W.T.P. No. 2
2. Polymers	no analysis	N.A.	N.A.	N.A.	Liquid polymers replaced after 2 to 3 months from manufacturer
Chemical feed res. concentrations					
1. Alum	Addition of stock solution	Alum feed res.	Solution made daily	Pipette and 1000 mL grad. cylinder	Daily change of solution
2. Polymer	Addition of stock solution	Polymer fed res.	Solution made daily	Pipette and 1000 mL grad. cylinder	Daily change of solution
Chemical feed rates	Volumetric feed from burrette	Alum Polymer	Hourly Hourly	Burrette and stopwatch	Volumetric meas.
Speed of mixing	Instrument	Shafts of mixers	Daily	Tachometer	Calibration with another instrument

[1] N.A. Not applicable.

[2] NBS National Bureau of Standards.

Perm - permanent

cysts retained. Sampling of the filter effluent was accomplished by passing the entire flow from the laboratory-scale rapid rate filter through the 5 micrometer pore size, 142 mm Nucleopore® polycarbonate membrane filter. About 20-40 liters were passed through the filter for each Giardia sampling; as much as 80 liters were passed through a filter during some test runs. This sampling technique was patterned after that described by Luchtel (1980). Of special interest is whether Giardia cysts remain on the membrane filter after washing. This was investigated by C. P. Hibler early in the investigation. Microscopic scans of the membrane filter after washing revealed no Giardia cysts. Complete review of the sampling procedure is given by Lange et al. (1984). Appendix J contains additional details on procurement of cysts, analysis techniques, detection limits, and results of related experiments.

Counting--

The Giardia cysts from the concentrated effluent samples were processed for microscopic counting by the micropipette technique. The cyst counting protocol was developed by Dr. C. P. Hibler, Professor of Pathology, Colorado State University. The results of the micropipette technique are reported by Dr. Hibler as the number of cysts found in the concentrated effluent sample. To obtain a cyst/liter concentration, this number is corrected for a sampling recovery efficiency and then divided by the volume of filter effluent passed through the membrane filter. When zero cysts are recovered, the Giardia cyst reported is in terms of detection limits. This is explained in Appendix J, after Bellamy et al. (1984).

Field-Scale Measurements and Quality Control

Measurements during operation of the field-scale pilot plant were similar to those obtained with the laboratory-scale pilot plant, with some deviations because of the differences in instruments or scale. The methods are described, but special attention is given to the problem of sampling flows. The quality control methods are incorporated in narrative format.

Flow Measurements--

Flows measurements were made volumetrically, and documented on the individual test data sheets. In this way, there were no discrepancies as to flow rates being obtained from pump settings.

Temperature--

Thermometers were standardized against a National Bureau of Standards Thermometer. Discrepancies were marked and the correction was applied when used.

Turbidity--

The measurement of turbidity was done by grab samples so that the samples could be measured using a Hach Ratio Turbidimeter Model 18900-10® This was the same as in the laboratory-scale testing. A photograph of the instrument is shown in Figure 18. Figure 16 shows that the influent samples were obtained after sufficient mixing of the suspension of Giardia

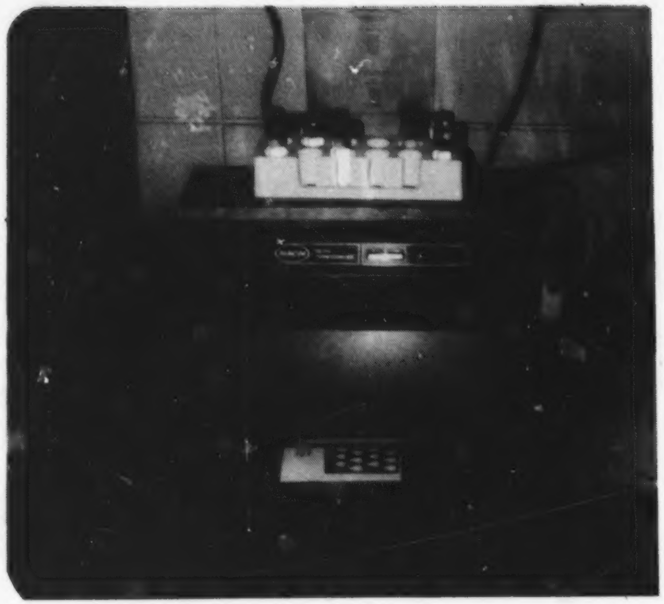


Figure 18. Hach ratio turbidimeter model 18900-10 used to measure turbidity.

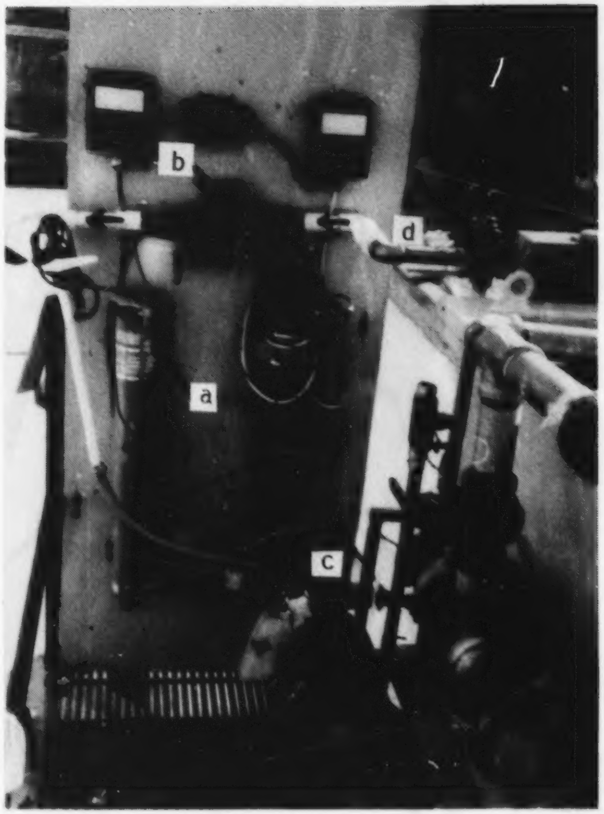


Figure 19. a) Hach flow-through turbidimeters, b) flow meter used to measure main flow, c) backwash valve #1, d) effluent flow control valve.

cyst and sewage with the influent stream. The effluent grab samples were obtained from the pipe discharging into the clear well. Figure 19 shows two Hach Flow-Through Turbidimeters, Model 1720-A®, used for monitoring purposes.

The Hach Ratio Turbidimeters, one at the Engineering Research Center and one at the Fort Collins Water Treatment Plant No. 1, were calibrated with formazin standards. They were checked daily with manufacturer-supplied reference solutions, and adjusted if needed. The flow-through meters were calibrated against the ratio turbidimeters.

Bacteria--

Influent and effluent coliform samples were obtained from the same ports as turbidity samples as shown in Figure 16. Coliform samples were obtained in autoclaved bottles and taken to the ERC microbiology laboratory, where culturing was in accordance with total coliform membrane filter procedures (Standard Methods, 1980). Standard plate counts were cultured at the same time.

The coliform source was wastewater primary effluent. The primary effluent was mixed with raw water and placed into the *Giardia* and coliform feed tank, 50 liter capacity, and then metered into the main flow stream along with the *Giardia* cysts.

For quality control, the autoclave operation was checked by the manufacturer, and all instruments and gauges were certified as operating correctly. In addition, the autoclave was checked each time with heat-sensitive tape.

The temperatures of the incubator and water bath were checked every other day when in use. The incubator was allowed to stabilize for two hours when temperature adjustments were made.

Bacterial Analyses--

Filter sterility was monitored by randomly choosing one of the 0.45 micrometer filters and placing it on a Petri dish of the standard coliform agar. This plate was then put through the same incubatiion as one of the other plates, but no water was filtered through it. The plate was then checked for growth after 24-hours, as were the other plates. Whenever possible, duplicate plates of each sample dilution were simultaneously prepared and counted. The average number between corresponding plates was the number reported. Once prepared, plates were refrigerated and kept for no longer than ten days.

Headloss Measurement--

Figure 20 shows the headloss board used to measure headloss across the filter. Water piezometers were used to measure head, with taps located above and below the filter media.

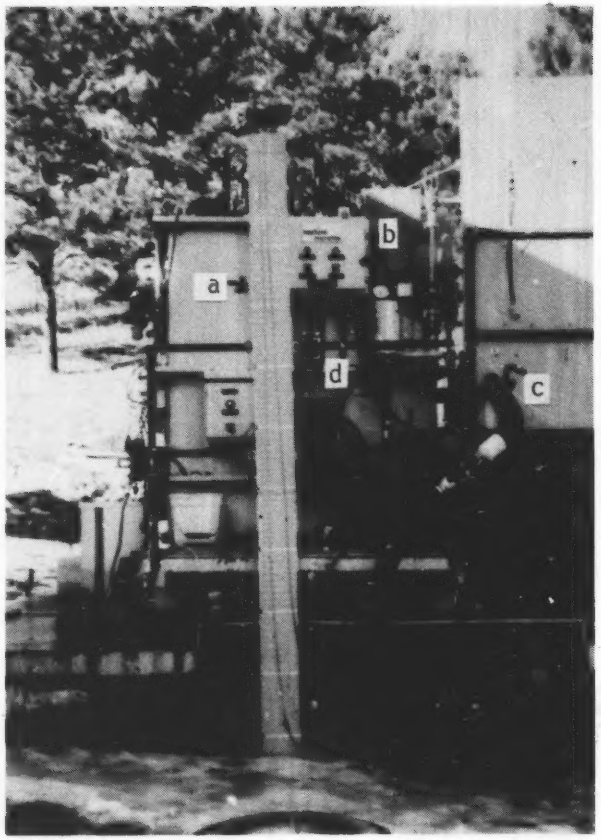


Figure 20. Side view of WATER BOY: a) headloss board with piezometers, b) main control panel, c) backwash hose, d) minor control panel.

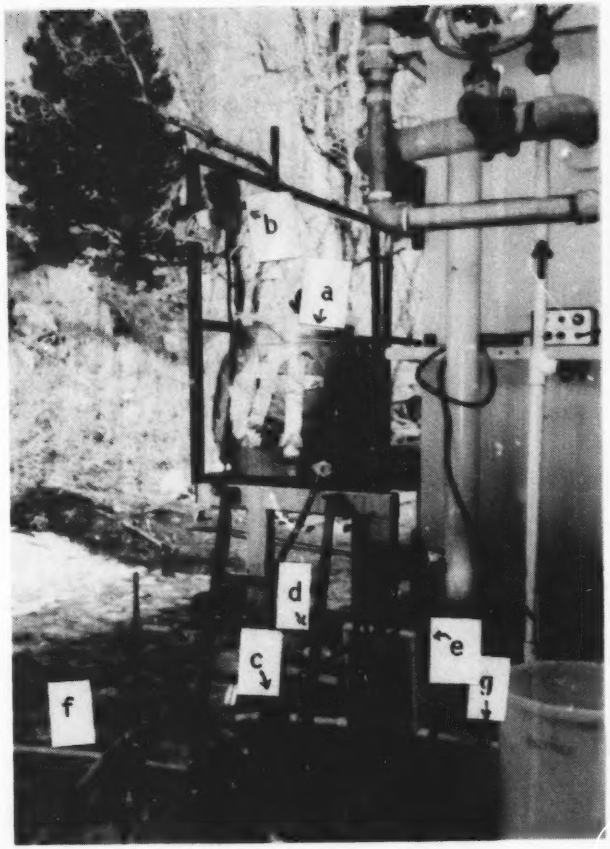


Figure 21. Contaminant feed system: a) batch tank, b) mixer, c) injection port, d) metering pump, e) four elbows for mixing contaminants with raw water, f) raw water line, g) influent sampling port for *Giardia*, coliforms, and turbidity.

Injection of Giardia cysts--

Figure 21 shows the contaminant injection system used to inject the suspension of raw water, dog feces suspension, and wastewater primary effluent. The suspension was agitated by a mixer while it was metered into the main flow stream by a positive displacement pump.

Giardia Sampling--

Sampling of Giardia cysts was done by passing a sampling stream, tapped from the influent and effluent pipes, respectively, through a membrane filter. Figure 16 shows the points in the flow scheme where the influent and effluent were sampled for Giardia. Figure 22 shows the membrane filter apparatus used to hold the 293 mm diameter, 5-micrometer pore size, polycarbonate filters made by Nucleopore Corporation.

The following steps enumerate the procedure to obtain either an influent, or effluent, Giardia sample. The only difference between an influent and an effluent sampling procedure was the point where the sampling stream was withdrawn from the main stream. Again, Figure 16 shows the Giardia cyst sampling ports.

i) Place membrane filter on stainless steel support plate, and securely screw on top of filter holder.

ii) Attach the Giardia sampling pump to the sampling port. The sampling pump is shown in Figure 23 as setup for sampling.

iii) Attach sampling pump to membrane filter.

iv) Open sampling port and turn on sampling pump.

v) Open air vent on membrane filter holder until water comes out, then close air vent. This bleeds air from filter holder.

vi) Collect the effluent from the filter holder in a calibrated tank. The flow rate used was about 2 gpm; this represents about 10 percent of the main flow stream.

vii) Pass the sampling stream through the filter holder until the headloss across membrane filter reaches about 20 psi, then turn-off pump and close port.

viii) Wait a few minutes until the water goes through the filter holder and into the calibrated tank.

ix) Record amount of water collected in calibrated tank.

x) Disconnect sampling pump from filter holder.

xi) Tilt membrane filter holder over a glass pyrex tray and open the holder slowly allowing excess water to flow into tray. This is shown in Figure 24.

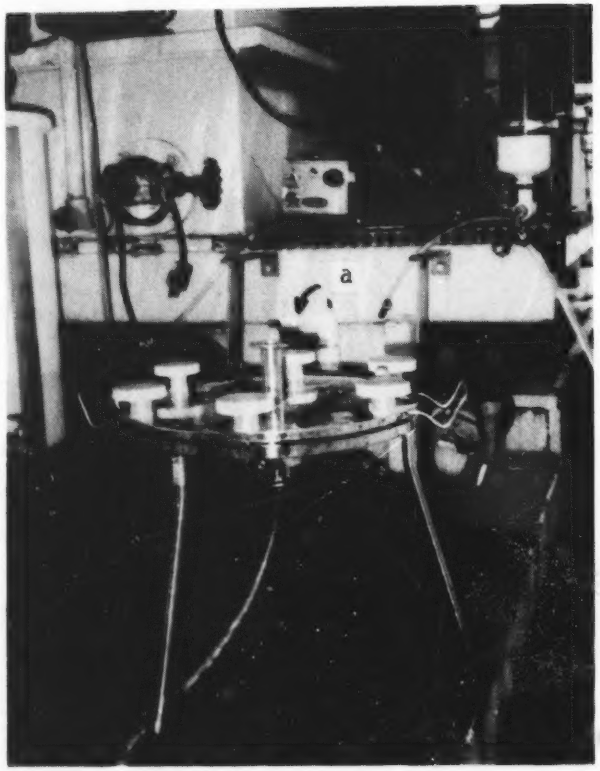


Figure 22. a) Membrane filter holder used to hold 5μm pore size, 293 mm diameter membrane filters.

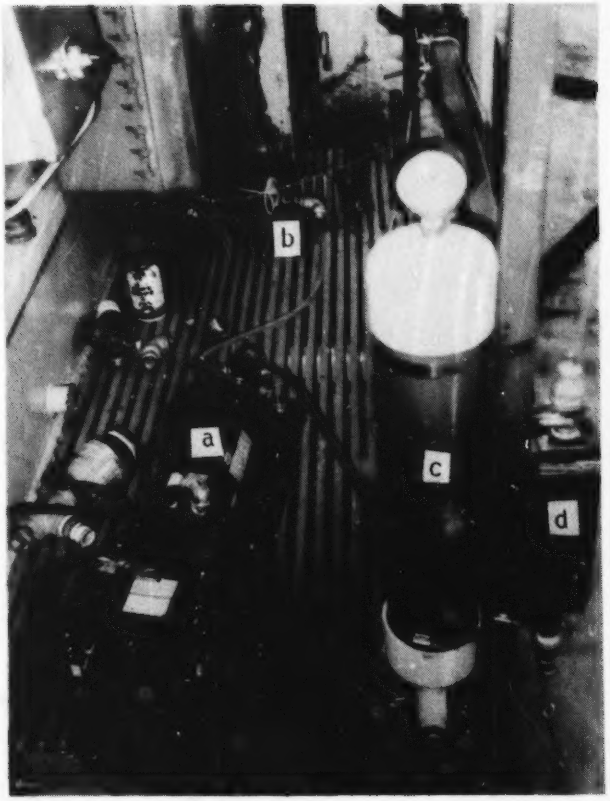


Figure 23. a) *Giardia* sampling pump, b) effluent sampling port for *Giardia*, c) dampener to stabilize the sampling stream, d) flow meter used to measure sampling flow rate.

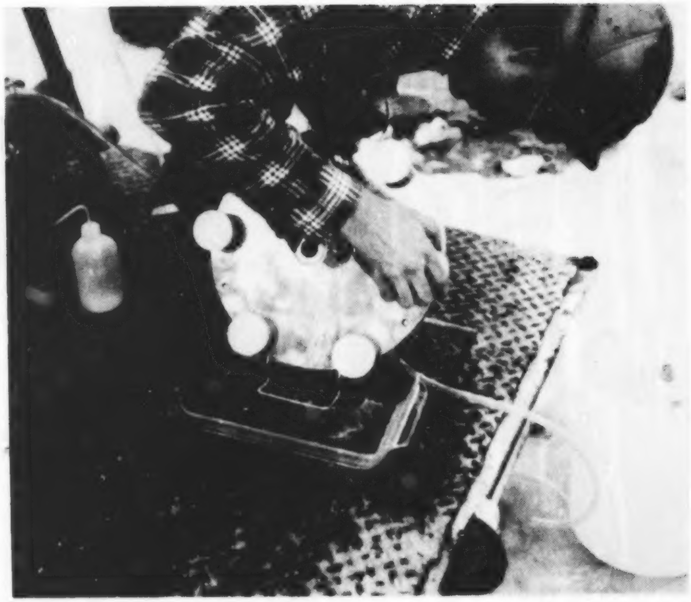


Figure 24. Membrane filter holder being opened allowing excess water to flow into pyrex tray.

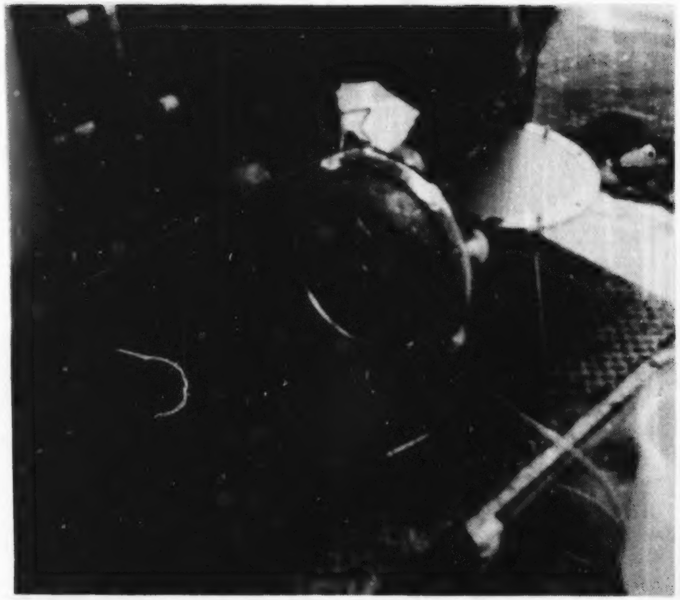


Figure 25. Top of membrane filter holder being rinsed, allowing wash water to flow into pyrex tray.

xii) Take top of filter holder off and rinse it, allowing the wash water to flow into the pyrex tray. Figure 25 shows this.

xiii) Tilt filter holder over tray and rinse cysts from membrane filter into tray. Shown in Figure 26.

xiv) Pour contents of tray into a mason jar labeled with sample number, as shown in Figure 27. Spray off tray to assure complete transfer of sample.

xv) Refrigerate sample immediately, and transport to Pathology Laboratory for counting of cysts recovered.

Giardia Measurement Quality Control--

The measurement of Giardia cysts was controlled by: i) insuring that the concentrations of cysts in the sampling streams were representative of the concentrations in the main flow stream; ii) sampling the influent water, after the cysts were injected, exactly as the effluent was sampled; and iii) performing "no chemical" Giardia cyst runs.

Representative samples were insured by following standard sampling procedures. For example, the sampling streams were taken from the center of the pipe, and the velocities of the sampling streams were made equal to the velocity of the main flow stream. Also, the influent sampling port was directed upstream to allow the "stream lines" direct access to the port.

The influent sample was obtained exactly as the effluent sample, i.e., both streams were run through the same pump, and then through the membrane filter holder. The sampling sequence was to sample the influent side first, then insert a new membrane filter and sample the effluent.

The "no chemical" Giardia cyst removal tests established references to compare removals when chemicals were used. In this way the effect of coagulant dosage could be evaluated.

DATA HANDLING

Aquisition of Data

During test runs all operating data were recorded on forms developed for this research. Data from analysis of samples were recorded on individual data sheets for the respective parameter being measured. Appendix E contains one sample of each data sheet used, with data from one test run shown for illustration.

Data Processing

Tables E-1 and E-2 contain all data for a given test run using the laboratory-scale pilot plant. These data were converted as necessary by

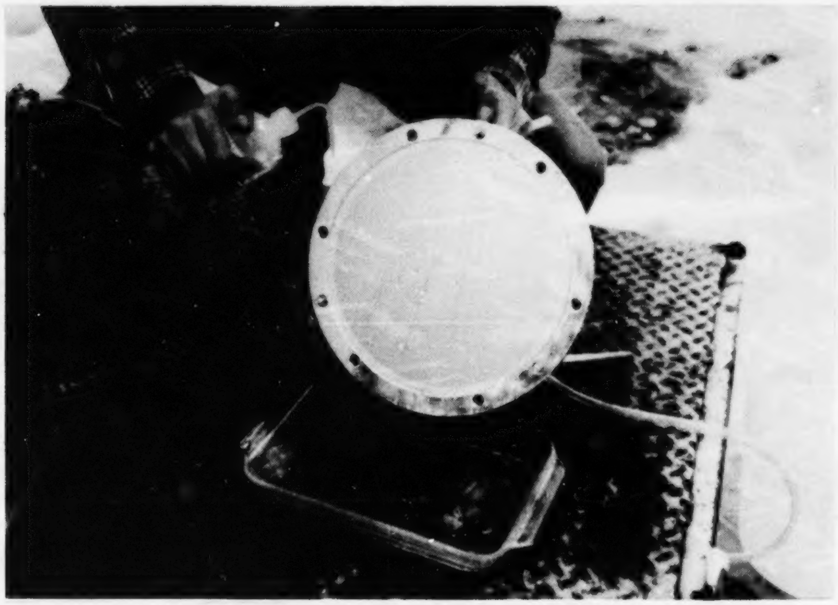


Figure 26. Membrane filter being rinsed. The cysts which were strained from the sampling stream are transferred to the pyrex tray.

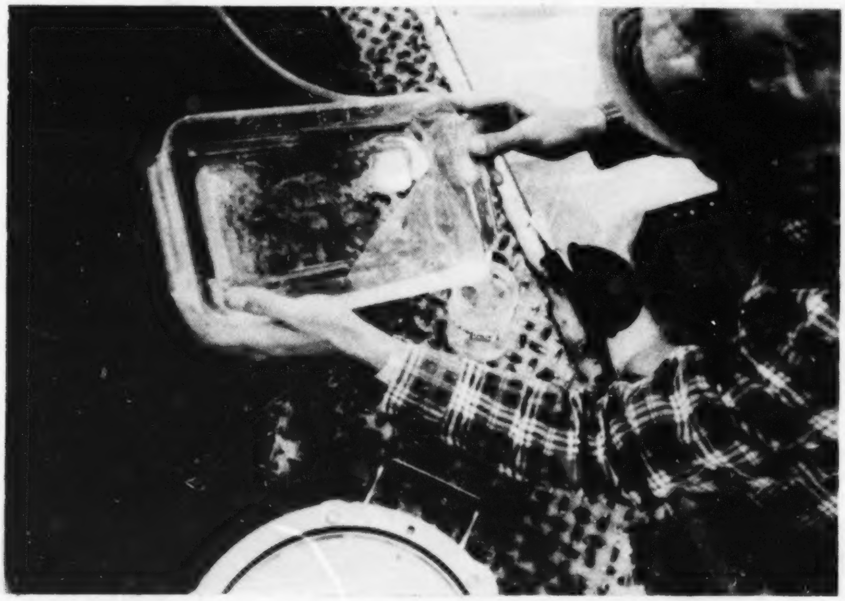


Figure 27. Transferring the contents of the pyrex tray to the mason jar.

hand calculation to the form needed. For example, the alum concentration in the raw water was obtained by multiplying the (flow of alum in milliliters liquid alum per minute) times (0.643 grams liquid alum as $Al_2(SO_4)_3.14H_2O$ per milliliter liquid alum) divided by (flow of raw water in milliliters per minute). The rpm of the paddle in the rapid mix basin and the temperature measurement were used to enter Figure C-7, which gave the corresponding G value. In this manner all data were converted to the form needed for developing relationships between variables of interest. These data were recorded in accordance with the format of a "master" data table, as one line of the table. Upon accumulation of several lines, e.g. several test runs, the data were transferred to a word processor file, where the table was allowed to grow.

Master Data Tables

All data were accumulated in a "master data table", which is Table A-1, in Appendix A for the lab-scale pilot plant results and Table B-1 in Appendix B for the field-scale pilot plant results. Table A-1 has 36 columns, grouped according to the following categories: test identification, influent water characteristics, chemical basin description, filter conditions, filter effluent data. Table A-1 in Appendix A is comprised of 12 sheets, which can be cut and taped together using the match lines indicated. The aggregated table is 4 sheets wide in accordance with the data categories. It is 3 sheets high to accomodate data from 178 test runs. Table B-1 can be taped together also, in the same manner.

For work using the field-scale pilot plant, data were recorded on forms shown in Table E-7. All the data for a given run was recorded on one of these sheets, including reduced data such as detected influent Giardia and coliform concentrations. In this way, any information on a run could be obtained by referring to the respective data sheet.

From these individual data sheets, the "master" table, Table B-1, was constructed. From this master table, all figures and tables illustrating the experimental testing were constructed.

Plots, Tables, and Statistical Analyses

Portions of the master tables, stored in a word processing file, was transferred to files in the CSU CYBER 720 computer, as needed for a particular analysis. For example, to ascertain the relation between turbidity and total coliform bacteria these data were transferred as "vectors" to a file in the CYBER. Once in the file, statistical analyses were performed as desired using package programs. Plots were also generated from the statistical analyses. Other parameters were transferred to the CYBER files in the same manner, and plots were generated to ascertain relationships. These plots were used as tools of analysis from which hand drawn graphs were developed, e.g. three-dimensional histogram plots.

SECTION 4

RESULTS AND DISCUSSION

This chapter first summarizes experimental results for removals of turbidity, standard plate count bacteria, total coliform bacteria, particles, and Giardia cysts by rapid rate filtration using low turbidity water. Second it describes relationship found between the above dependent variables and process variables. The process variables examined included: coagulants selection, dosages of coagulant, coagulant sequence, filtration treatment train, filtration media, filtration rate, temperature, and run time. And third, it examines relationships between removals of Giardia cysts and removals of turbidity, total coliform bacteria, etc., in an effort to find a surrogate indicator for the former. All results for these first three activities were obtained using the laboratory-scale rapid rate filtration pilot plant. Finally, results obtained using the field-scale pilot plant are summarized in the last section.

Some 178 test runs were performed over an 18 month period using the laboratory-scale pilot plant, and some 144 test runs were performed using the field-scale pilot plant. Table A-1 in Appendix A is a "master" table summarizing all results obtained using the laboratory-scale pilot plant. Table B-1 in Appendix B is a similar "master" table summarizing all resuls from the field-scale pilot plant testing. Table A-2 shows Giardia cyst removal efficiencies corrected for detection limits. All tables and graphs used in this chapter were constructed from data contained in Tables A-1, A-2, and B-1, respectively.

REMOVALS - LABORATORY-SCALE PILOT PLANT

Table 10 summarizes percent removals of turbidity, standard plate count bacteria, total coliform bacteria, particles, and Giardia cysts for low turbidity water at low temperatures, e.g. 2°C to 4°C. Results of 21 test runs are shown for three categories of chemical pretreatment: (1) "none," e.g. no chemicals were used, (2) "nonoptimum," e.g. a nonoptimum chemical dose was used as measured by turbidity removal, (3) "optimum," e.g. an optimum chemical dose was used as measured by turbidity removal. Samples were taken after one hour of a test run for "none," and 2 to 4 hours for "nonoptimum" and "optimum" chemical dose. Two sources of low turbidity water were used in the testing: (1) natural low turbidity water from the Cache La Poudre River, and (2) artificial low turbidity water produced by filtration of Horsetooth Reservoir water by diatomaceous earth filtration. Filtration rates ranged from 8.2 cm/min to 41.4 cm/min (10 gpm/ft^2). Both dual media

Table 10. Effect of chemical pretreatment on removal of turbidity, standard plate count bacteria, total coliform bacteria, particles and Giardia cysts for low turbidity artificial water, and low turbidity Cache La Poudre River water, by "in-line" rapid sand filtration[1/,2/,3/].

Run No.	Conditions				Pretreatment			Filter Effectiveness				
	Filter		Water		Chemicals used			Percent Removal				
	V (cm/min) [4/]	Media[5/]	Source[6/]	Temp. (°C)	Dosage Category[7/]	Species	Dosage (mg/l)	Turbidity	Standard Plate Count	Total Coliform	Particle Count	Giardia Cysts
46	8.46	Sand(L)	HDE	3.0	None	None	0.0	27.3	-51.3	13.8	85.8	7.6
47	22.59	Dual(L)	HDE	3.0	None	None	0.0	-72.4	-66.6	25.0	98.7	96.3
49	22.20	Sand(L)	HDE	2.0	None	None	0.0	-13.8	20.6	60.0	98.6	>99.9
48	8.26	Dual(L)	HDE	3.0	None	None	0.0	-18.2	-108.2	38.4	94.2	99.9
119	41.40	Dual(F)	CLP	3.0	None	None	0.0	18.8	9.7	5.3	89.7	41.9
120	32.00	Dual(F)	CLP	3.0	None	None	0.0	18.8	16.1	-7.5	85.8	36.4
121	20.70	Dual(F)	CLP	3.0	None	None	0.0	18.1	16.1	1.1	82.2	36.3
122	9.60	Dual(F)	CLP	3.0	None	None	0.0	15.6	99.6	99.9	81.2	68.3
69	22.69	Dual(L)	HDE	3.0	Nonoptimum	alum/573c	15.0/1.1	73.6	78.8	99.9	-142.4	99.2
82	22.45	Dual(L)	HDE	3.0	Nonoptimum	alum/572c	8.8/0.6	61.0	38.0	- 8/	99.6	- 8/
114	7.8	Dual(F)	CLP	3.0	Nonoptimum	alum/572c	23.7/1.2	69.0	96.8	99.0	58.9	95.3
50	8.20	Sand(L)	HDE	4.0	Optimum	alum/572c	2.1/0.9	88.9	82.3	>99.9	98.6	97.8
51	23.48	Dual(L)	HDE	3.0	Optimum	alum/572c	4.1/1.7	86.1	85.4	83.0	98.9	99.1
52	8.45	Dual(L)	HDE	4.0	Optimum	alum/572c	2.1/1.2	91.7	95.6	>99.9	99.2	99.7
53	23.19	Sand(L)	HDE	4.0	Optimum	alum/572c	3.4/2.1	82.6	- 8/	>99.9	93.8	99.5
70	22.20	Dual(L)	HDE	3.0	Optimum	alum/573c	7.6/1.3	88.7	98.4	99.5	81.9	99.4
81	8.35	Dual(L)	HDE	3.0	Optimum	alum/572c	6.8/0.9	85.4	97.8	99.9	98.3	- 8/
104b	8.26	Dual(F)	CLP	3.5	Optimum	alum/572c	13.4/0.6	82.4	99.5	79.8	98.6	98.7
106	8.47	Dual(F)	CLP	3.5	Optimum	8102N	0.5	-43.1	99.9	>99.9	87.0	39.5
107b	8.38	Dual(F)	CLP	3.0	Optimum	alum/572c	11.3/0.5	92.7	96.7	90.0	95.4	>99.9
118	9.37	Dual(F)	CLP	3.0	Optimum	alum/572c	23.7/1.4	85.5	98.4	99.4	- 8/	97.6

1/ Abstracted from Table A-1 and Table A-2, Appendix A.

2/ Artificial water was obtained by Diatomaceous Earth filtration of Horsetooth Reservoir water, filtered water turbidity ranged from 0.2 to 0.6 NTU. See also footnote 6.

3/ The term "In-Line" filtration is the designation for treatment train comprised of rapid mix and filtration, e.g. no flocculation or sedimentation.

4/ The term V is used as hydraulic loading rate which equals flow divided by area of filter.

5/ Sand (L) was obtained from Loveland Treatment Plant at Big Thompson Canyon. Bed depth was 76cm. Dual (L) means the bed was comprised of 30 cm sand from Loveland and 45 cm anthracite having trad name Philterkal Special No.1(produced by Reading Anthracite Coal Company. Pottsville, PA. 17901). Dual(F) Fort Collins means that the bed was comprised of 30 cm sand was obtained from Fort Collins Treatment Plant No.2 and 45 cm Philterkal Special No.1(R) anthracite.

6/ HDE is water obtained from Horsetooth Reservoir, filtered by Diatomaceous Earth to give low turbidity, e.g. 0.2 to 0.6 NTU CLP is low turbidity raw water obtained from the Cache La Poudre River during the period September to April when raw water turbidity was generally 0.4 to 0.7 NTU.

7/ "Optimum" and "none optimum", are designated of coagulant dosages producing turbidities of filterd water which are minimum and greater than minimum, respectively.

8/ No sample taken.

and sand was used. Results are described for each of the dependent variables in the paragraphs following.

Turbidity

Table 10 shows the effect of chemical pretreatment on turbidity removal. For the eight "none" coagulant dosage tests, i.e. coagulant chemicals were not added, turbidity removals were -72 to 19 percent. With a "nonoptimum" dosage of chemicals removals increased to the 61 to 74 percent range. But if "optimum" dosage was used percent removals were 83 to 93. Finished water turbidity was about 0.05 NTU, generally.

Standard Plate Count Bacteria

Table 10 shows that the standard plate count bacteria removal percentages range from -108 to 20 for seven of the eight test performed without chemical addition, with the eighth test showing 99 percent removal. For three "nonoptimum" test runs, removal percentages ranged from 38 to 97 percent. For the nine test runs, using optimum coagulant dosages, removal pecentages ranged from 82 to 99.9 percent. These results also illustrate that high removals can be expected for chemical dosages that are "optimum."

Total Coliform Bacteria

Table 10 shows that for those tests performed with no chemical pretreatment the total coliform bacteria removal percentages ranged from -7 to 99.9 percent. For the "nonoptimum" chemical dosages removals were greater than 99 percent. For the nine test runs using "optimum" chemical dosages removal percentages ranged from 80 to greater than 99.9 percent. Most were greater than 99 percent.

Particles

Table 10 shows percent removals of particles in the 2.52 to 50.8 micrometer (µm) size range. For the no chemical pretreatment condition the removal percentages ranged from 81 to 99 percent. For the "nonoptimum" chemical dosages, particle removals ranged from -142 to 99.6. Table 10 also shows that for the nine "optimum" coagulant dosages, removal percentages ranged from 82 to 99 percent. The use of 8102N used as a filter aid gave a removal of 87.0 percent. These results, show high removals of particles when no chemicals were used, which are inconsistent with turbidity and bacteria removal results. These results indicate that particle counting was not useful as an indicator of filtration perfomance.

Giardia Cysts

Table 10 shows percent removals of *Giardia* cysts, based on the detected cysts concentrations (Table A-2), for twenty test runs. The table shows that with no chemical pretreatment the removal percentages for five test runs ranged from 8 to 68. But for three test runs removals were greater than 96 percent. It should be noted that cyst characteristics are different from one batch to another, e.g. some are hardy and retain their shape for several weeks while others deteriorate within days. Dr. Hibler indicated that the cysts used in Runs 47, 48, 49 were a batch that deteriorated quickly, as determined by the sample maintained under refrigeration as a control. This would account for the high "removals" noted. For other runs the control cysts showed no such deterioration. At "nonoptimum" chemical dosages removal percentages ranged from 95 to 99 percent. For eight test performed with "optimum" chemical dosages, the Giardia cysts removals were greater than 98 percent, with five exceeding 99 pecent. Using the filter aid 8102N removal was 39.5 percent.

Of special interest, these results show that with proper chemical pretreatment, rapid rate filtration will remove greater than 99.9 percent of Giardia cysts. Removals of Giardia cysts exceeded 97 percent for all filtration conditions imposed when optimum chemical dosages were used.

The data show that for optimum chemical pretreatment dosages, removals of turbidity, standard plate count bacteria, total coliform bacteria, particles, and Giardia cysts are uniformly high, e.g. greater than 80 percent for turbidity and 98 percent for all other parameters. For "nonoptimum" chemical dosages results are more variable with both high and low removals. For the "none," or no chemical pretreatment condition, removals are markedly lower for all parameters except particles, which ranged from 81 to 99 percent.

The results in Table 10 show that rapid rate filtration will work as a simple strainer when no chemicals are used, and will pass appreciable percentages of turbidity, bacteria, and Giardia cysts. They illustrate also the critical importance of proper chemical coagulation. It is imperative to select effective chemicals and to use proper dosages.

The removals of particles were high even when no chemicals were used, which was at variance with the results for the other parameters. Therefore, particles are felt to be not useful as a measure of filtration effectiveness, for the conditions examined.

Table 10 shows also that for "optimum" chemical dosages, it makes little difference whether single media or dual media is used. Neither is there any noticeable effect of hydraulic loading rate. The over-riding concern in treating low turbidity waters should be with determining which chemicals are effective and their dosages.

EFFECT OF PROCESS VARIABLES

The effect of process variables was ascertained by changing the magnitudes of each through a range of values while all other variables were maintained constant, using the laboratory-scale pilot plant. The process variables investigated were: coagulants, dosages of coagulants, sequence of coagulant addition, mode of filtration, comparison of single and dual media, filtration rate, temperature, run time.

Removal of turbidity was the principle focus because it was found to be indicative of removals of both bacteria and *Giardia* cysts. Removals of the latter were measured also during this phase of the investigation, but not for every test. The labor involved for measurements of bacteria and *Giardia* cysts was a concern, but the addition of *Giardia* cysts also caused changes in turbidity of the raw water, which was not acceptable for many of the tests involving low turbidity water. This section reviews the results of the effect of process variables on turbidity removal, and on removals of bacteria and *Giardia* cysts.

Coagulant Selection

Figure 28 compares five polymers with respect to effluent turbidity produced by means of jar-filter testing (see Choi, 1983). Clearly 572C shows the lowest effluent turbidity, e.g. 0.05 NTU. The other polymers shown could be as effective at other combinations of alum-polymer dosages. Such testing

Test Conditions
Run number(s) : 17,33
Raw water turbidity : 0.49 NTU
Temperature : 18C
Primary coagulant : Run 17 and Run 33 1.5 mg/L alum.
Secondary coagulant : Run 17 and Run 33 0.5 mg/L polymer.

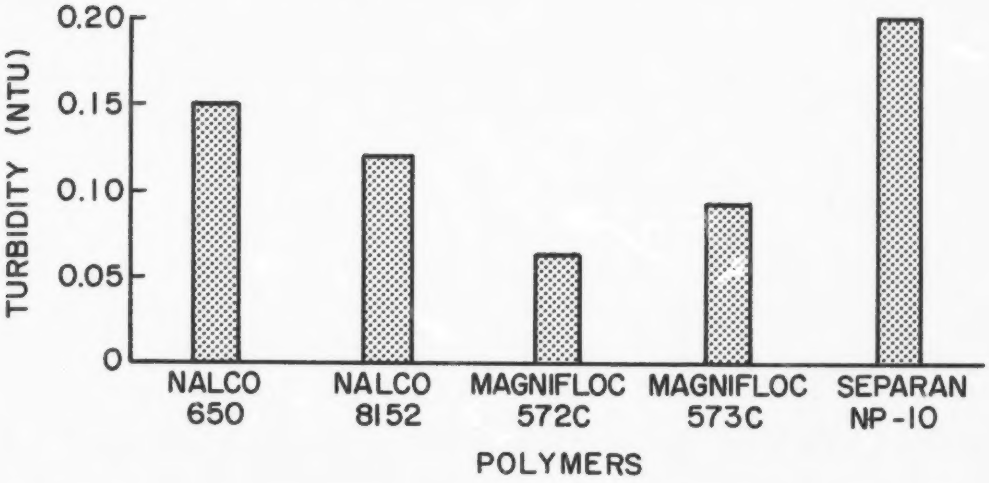


Figure 28. Comparison of turbidity reduction in jar-filtration testing by five polymers (Choi, 1983).

was not done, however, as the effort was limited in scope toward finding only one or two polymers which might be effective in filtration of low turbidity waters. Nine polymers were tested in this manner. They are listed in Table I-1, Appendix I.

Further testing of polymers was done using the laboratory scale rapid rate filtration pilot plant. The results, all of which are given in Table A-1, confirmed that Magnifloc 572C® and Magnifloc 573C® were effective in filtration of low turbidity waters.

Table 11, abstracted from Table A-1 and Table A-2, shows the percent removals, as data are available, for chemical pretreatment conditions indicated. Seven such conditions are indicated for four polymers used alone and used with alum. Also results are shown using alum alone, and the condition of "no chemicals". The data shown are for all conditions of hydraulic loading rate, media, temperature, and source of water. The data show very clearly that without chemical pretreatment, removals are quite low for all parameters, e.g. nominally about 30 to 60 percent removals. The polymers 572C and 573C used alone are not highly effective either, but results are variable. Neither is alum alone effective. The two polymers 572C or 573C with alum, however, are highly effective with removals generally greater than 80 percent for turbidity, more than 90 percent for standard plate count bacteria, 99 percent for total coliform bacteria, and 95 percent for *Giardia* cysts.

Figure 11 is a histogram showing percent removal of turbidity for nine coagulant conditions. This figure is a visual way to show the data in Table 11. It shows clearly the percent removal of turbidity is low when no chemical pretreatment is used, compared with using alum and Magnifloc 572C® or alum and Magnifloc 573C® for pretreatment. Figure 12 is a histogram showing percent removal of *Giardia* cysts for the same nine coagulation conditions. This figure is another plot for the data shown in Table 11. It illustrates further that with no chemical pretreatment the percent removal of *Giardia* cysts ranged from 40 to 80 percent, except for five test runs. Using alum and either Magnifloc 572C® or Magnifloc 573C® gave more than 95 percent of *Giardia* cyst removal in most of the test runs. These data show the importance of polymer selection in filtration of low turbidity water, and that a combination of the polymer and alum is necessary.

Dosages of Coagulants

Based upon the screening of polymers, described earlier , two, Magnifloc 572C and Magnifloc 573C, were selected for further testing to determine their effectiveness in removal of turbidity, for the turbidity range of <1 NTU, when used in combination with alum. The premise was that if substantial turbidity removal occurred then high removal efficiencies would also occur for bacteria and *Giardia* cysts. Thus the initial search was to ascertain the ranges of chemical dosages, for alum and polymer, to remove high percentages of turbidity.

Table 11. Removals of turbidity,, standard plate count bacteria, total coliform bacteria, and Giardia cysts, for different conditions of chemical pretreatment. Data shown are for low turbidity raw water, e.g. less than 1.5 NTU and for all conditions of hydraulic loading rate, media temperature, and source of water.

Chemical Species	Percent Removal			
	Turbidity	Standard Plate Count Bateria	Total Coliform Bacteria	Giardia Cyst
No chemical	27,-73,-18,-14,23	-51,-67,-1.8,20,x	14,-25,38,60,x	74,96,100,100,94
	15,-2,-2,19,19	x,x,x,10,16	x,x,x,5,-7	x,x,x42,36
	18,16,26,23,3	16,96,-23,31,-10	1,99.9,0,0,92	36,68,49,72,98
	13,-5,27,28,1	24,-77,-25,-15,14	75,-25,48,40,90	x,x,x,x,x
Alum	-62,-144,-62	48,-600,-1.5	3,x,87	x,x,x
8102 N	-43,89,92,84,89	99.9,91,99,94,96	99.9,x,x,88,83	40,x,x,x,x
	93,90,93,98,99	94,97,95,97,97	85,86,90,99,99	x,x,x,x,x
	81	x	x	x
8100N	17,27	x,x	66,65	x,x
8170 N	14,43	92,84	x,x	x,x
8181 N	63,34,20,27,87	x,x,70,87,87	x,x,45,28,84	x,x,x,x,x
	93,93	87,34	>99,97	x,x
650	3	95	3	x
572C	58,53,-32,-5,-56	97,x,91,62,56	100,x,99,99,92	x,x,x,x,99.9
	-27,18,35	-233,-77,90	x,-87,98	x,x,x
573C	74,53	46,85	99,71	x,x
Alum and 8102N	39,-3,-17,74	43,96,95,80	30,99,99,>99	95,100,91,100
NP10, Alum	80	x	x	x
Alum and 572C	90,96,96,97,77	99,98,99,99,x	98,99,99,99,x	x,x,x,x,x
	59,86,82,77,87	63,99.9,94,86,x	99,99,99,96,x	x,x,x,x,x
	81,87,84,84,79	96,x,95,42,86	x,x,99.9,99.9,96	x,x,x,x,x
	86,91,89,91,89	x,x,x,x,82	x,x,x,x,99.9	100,100,100,92,98
	86,92,83,94,79	85,96,x,90,x	80,99.9,99.9,99.9,x	100,100,100,87,x
	83,85,61,86,60	94,98,38,x,93	99.9,99.9,99.9,x,90	x,x,x,x,99.7
	93,92,90,89,85	97,98,63,98,94	90,x,98,97,99	99.9,x,99.8,x,x
	95,56,62,38,61	96,96,99,0,97	99,99,99,99.9,99.9	x,91,97,95,95
	79,82,15,83,-85	99.3,99.8,78,98,83	99.9,99.9,99.6,99,99.9	85,97,97,98,x
	-177,-48,78,-118,-41	76,92,83,79,75	99,99,x,x,x	x,x,x,x,x
	89,89,91,85,52	-542,98,98,78,83	96,97,99.5,99,93	84,94,x,x,x
	78,-30,30,70,86	93,95,92,93,96	99.8,98,99.6,99.7,99.5	x,x,x,x,x
	83,85	92,99.7	99.9,99.9	x,x
Alum and 573C	77,81,62,53,88	99.9,75,84,-8,89	99,98,98,99,x	x,x,x,x,x
	89,90,-0.7,73,89	91,87,17,79,98	x,99.9,99.9,99.9,99	99,99.9,94,99,99
	96,95,-15,94,61	99,99,18,98,x	99.9,99.9,x,99.9,x	99.9,99.9,x,99.5,96
	74,17,82,42,85	99.9,50,99,98,84	99.9,-24,80,45,91	99.5,97,99,x,x
	93,80,97,96,85	41,x,32,95,x	99,x,x,x,x	x,x,x,x,x
	89,54,65,74,79	x,23,x,96,-98	100,99,99,99,98	x,x,x,x,x

x = No data.

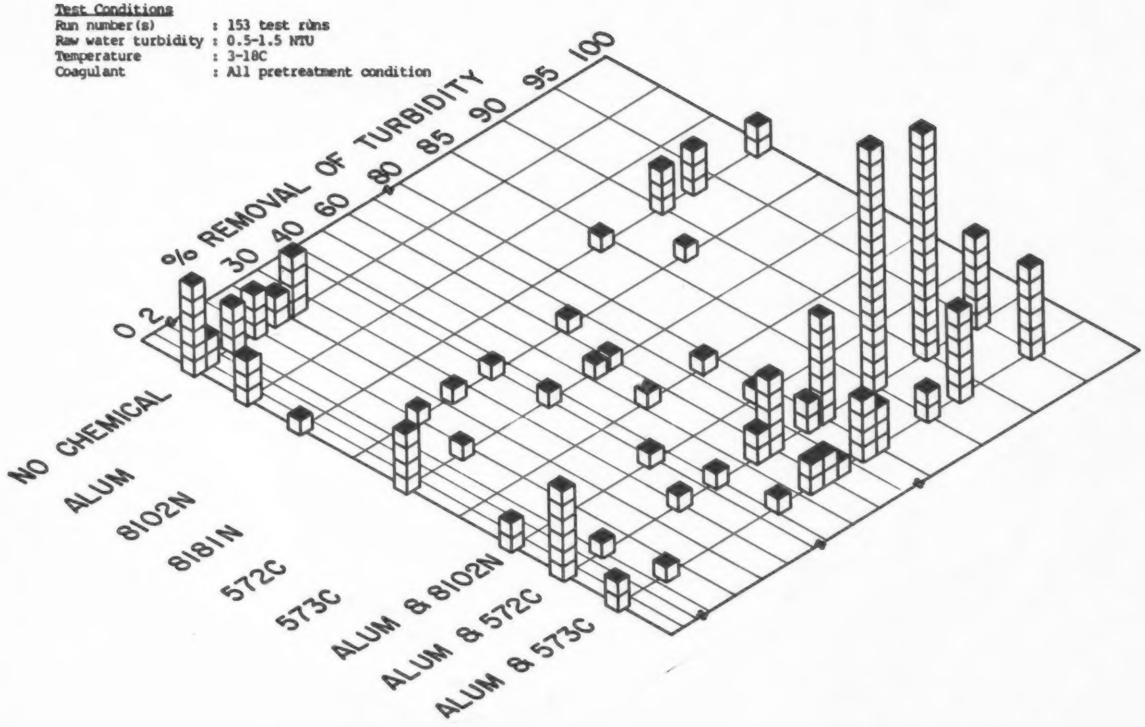


Figure 29. Histogram of turbidity percent removal and coagulant tested, using laboratory-scale rapid rate pilot plant. Each block represents one measurement set.

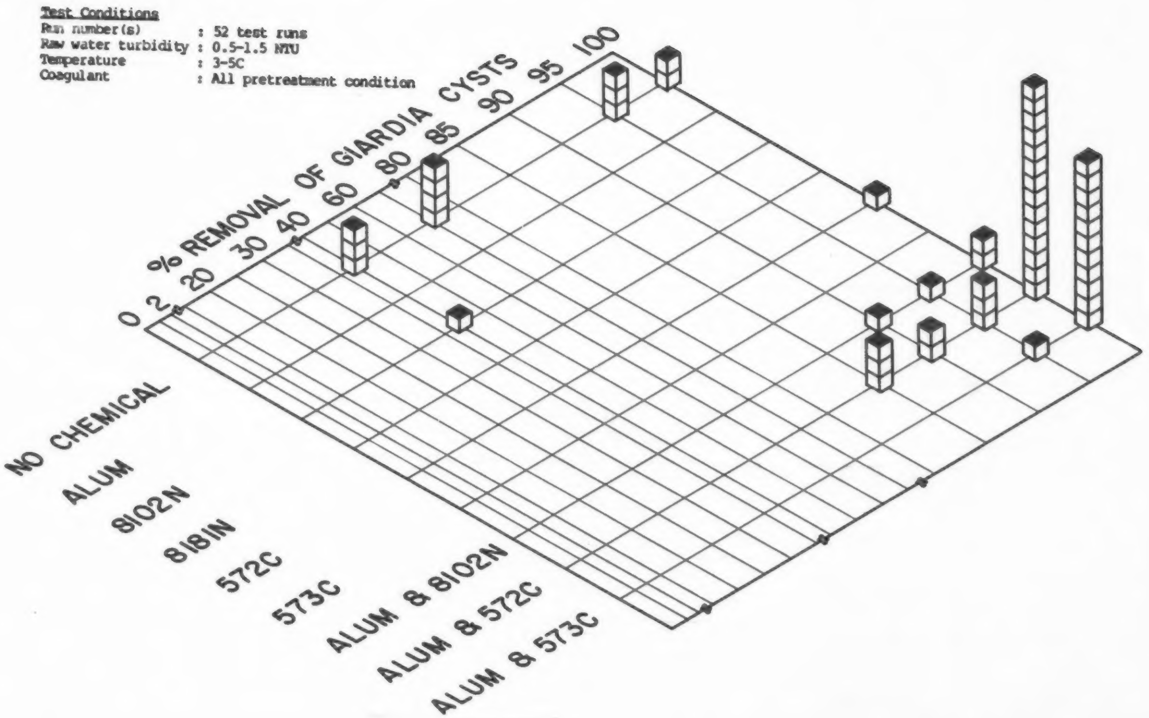


Figure 30. Histogram of Giardia cysts percent removal and coagulant tested, for laboratory-scale rapid rate pilot plant. Each block represents one measurement set.

The search was initiated using jar-filter testing for guidance. Dosages of alum and Magnifloc 572C® were found which resulted in turbidity reductions from about 0.5 NTU to 0.05 NTU. These dosages were then tested further, using the laboratory-scale pilot plant. The same dosage ranges also resulted in effluent turbidity levels of about 0.05 NTU.

At the same time, testing was continued using total coliform bacteria and Giardia cysts. Reductions in both were found to be greater than 95 percent when turbidity reductions were greater than 80 percent.

As test runs continued, data were accumulated for a wider range of alum-polymer dosages. While a turbidity response surface was not "mapped" systematically by this accumulation of points, nevertheless it became feasible to do so. Figure 31 indicates a response surface for filtration effluent turbidity versus dosages of alum and Magnifloc 572C. The shaded bars were obtained using the lab-scale pilot plant. The open bars were obtained by jar-filter testing. Table 12 gives the coordinates for the data points in Figure 31.

Figure 31 shows that coagulation and filtration using alum alone or polymer alone is not efficient. Turbidities of filtered water are in the same range as raw turbidities, or they may be higher. Raw water turbidities generally were less than 1 NTU. But jar-filtration testing (Run 39, 6/7/83) showed that continuation of alum addition caused increasing turbidity with a peak of about 4.8 NTU, followed by rapid decline to 0.3 NTU at 40 mg/L alum (with no polymer). These test run results are not shown in Figure 31 because they are off-scale. The results are similar to practice at the Dillon water treatment plant where 50 mg/L alum and 25 mg/L sodium carbonate are used to produce filtered water turbidity of about 0.1 NTU. When alum was used in combination with Magnifloc 572C, however, turbidities were reduced to 0.05 to 0.10 NTU. The alum dosage needed was only 3-7 mg/L. Regardless of the alum-polymer dosage combination, the filtered water turbidity remained in the 0.05 to 0.10 NTU range as seen in Figure 31. Thus virtually any dosage combination of alum and 572C will reduce the filtered water turbidity about 80 to 90 percent when compared with raw water. This means that one does not have to be too careful with dosages from the standpoint of efficiency, e.g. ratio of filtered water turbidity to raw water turbidity. From the standpoint of economics, however, the lowest dosages should be used.

Figure 31 shows also that the results obtained using the lab scale rapid rate filtration pilot plant were comparable with results using the bench scale jar-filtration testing. The use of the jar-filter testing is discussed elsewhere.

The effect of polymer dosage, for a range of alum dosages from 0.2 to 15.0 mg/L, on removal of Giardia cysts is shown in Figure 32, which is a histogram showing the numbers of observations for given percent removals of Giardia cysts and polymer dosages. It shows that removals exceeded 99 percent, with only three exceptions. The polymer dosages used most often in this work were 1 to 2 mg/L. This dosage is recommended because the data in

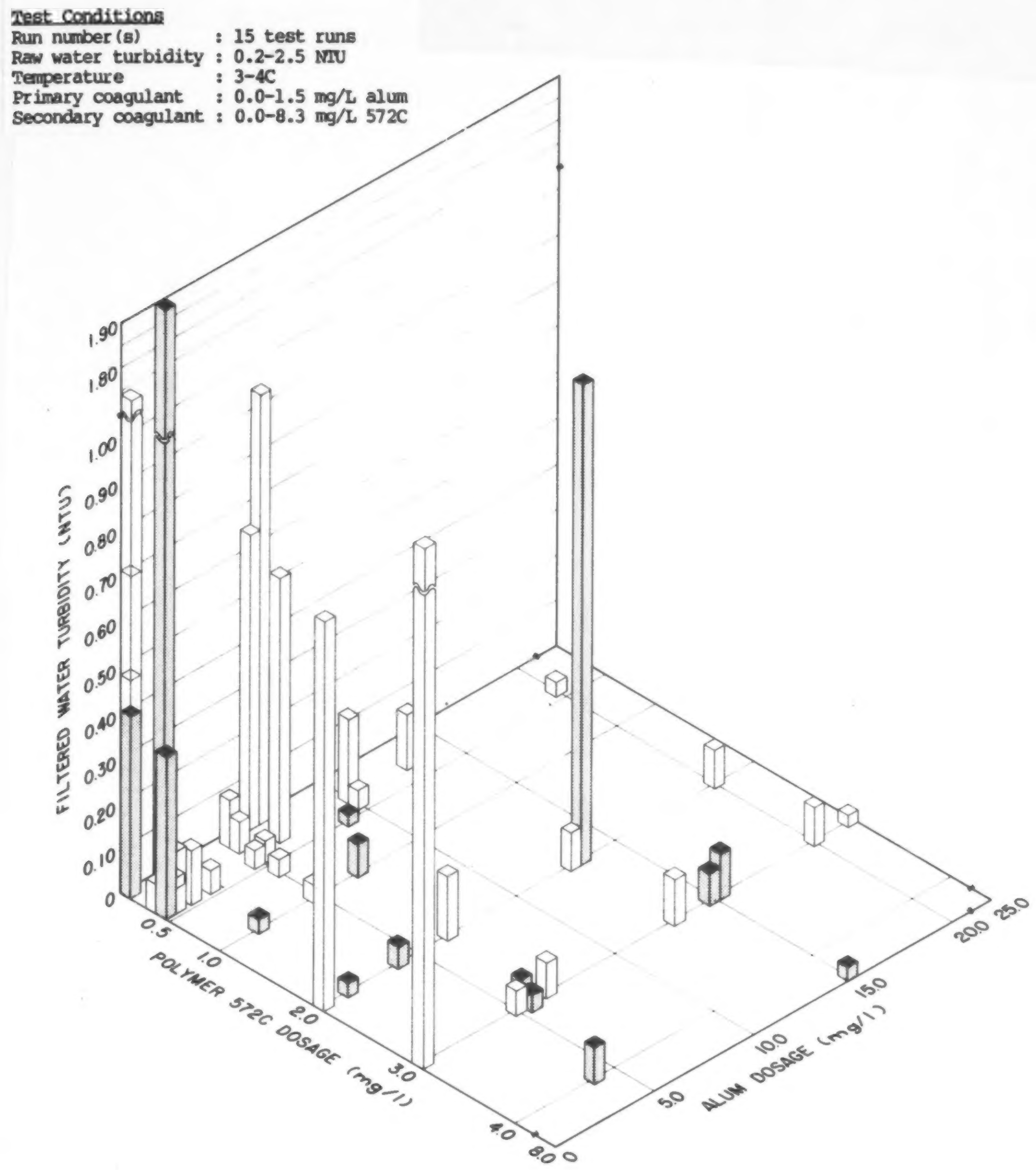


Figure 31. Turbidity of filtered water for various combinations of alum and polymer (Magnifloc 572C). Shaded bars were obtained using laboratory-scale rapid rate pilot plant. Open bars were obtained using jar-filtration apparatus. All tests were conducted at 3-5°C. Raw water turbidities were less than 1 NTU with exceptions as noted in Table 12.

Table 12. Filter effluent turbidities for low turbidity low temperature water with pretreatment using alum and Magnifloc 572C polymer. Data were obtained using sources indicated.

Run No.	Source of Data	Apparatus	Raw Water Turbidity (NTU)	Alum as $Al_2(SO_4)_3\ 14H_2O$ (mg/L)	Polymer Magnifloc 572C (mg/L)	Filter Effluent Turbidity (NTU)
13	EPA Report,	Jar test	2.20	0.00	0.0	1.74
13	June 1983[1]	Jar test	2.20	2.00	3.0	1.79
13	"	Jar test	2.20	6.43	3.0	0.08
13	"	Jar test	2.20	12.9	3.0	0.10
13	"	Jar test	2.20	19.3	3.0	0.08
13	"	Jar test	2.20	25.7	3.0	0.23
19	"	Jar test	0.83	0.00	0.0	0.48
19	"	Jar test	0.83	0.00	2.0	0.86
19	"	Jar test	0.83	6.43	0.0	0.65
19	"	Jar test	0.83	6.43	2.0	0.14
19	"	Jar test	0.83	12.90	2.0	0.08
19	"	Jar test	0.83	19.30	2.0	0.08
21	"	Jar test	0.66	0.00	0.0	0.71
21	"	Jar test	0.66	0.00	0.3	0.66
21	"	Jar test	0.66	6.43	0.0	0.94
21	"	Jar test	0.66	6.43	0.3	0.58
21	"	Jar test	0.66	9.65	0.3	0.18
21	"	Jar test	0.66	12.90	0.3	0.12
68	Choi	Jar test	0.40	0.5	0.4	0.14
68	Thesis[2]	Jar test	0.40	1.5	0.4	0.2
68	1983	Jar test	0.40	2.5	0.4	0.05
68	"	Jar test	0.40	5.0	0.4	0.05
68	"	Jar test	0.40	10.0	0.4	0.04
68	"	Jar test	0.40	20.0	0.4	0.03
75	Choi	Jar test	0.40	5.0	0.1	0.11
75	Thesis	Jar test	0.40	5.0	0.2	0.07
75	1983	Jar test	0.40	5.0	0.4	0.04
75	"	Jar test	0.40	5.0	0.6	0.04
75	"	Jar test	0.40	5.0	1.0	0.04
75	"	Jar test	0.40	5.0	3.0	0.53
79	"	Jar test	0.40	1.5	0.2	0.25
37	Master[3]	Pilot	0.19	15.30	8.33	0.03
38	Table	Plant	0.19	1.47	1.97	0.03
40	"	"	0.19	5.57	2.59	0.04
43	"	"	0.64	5.48	2.81	0.06
44	"	"	0.76	3.55	3.85	0.08
51	"	"	0.36	4.08	1.68	0.05
52	"	"	0.36	2.07	1.17	0.03
81	"	"	0.48	6.70	0.80	0.07
82	"	"	0.59	8.82	0.55	0.23
84	"	"	2.20	12.60	1.97	1.05
87A	"	"	2.50	14.70	2.40	0.10
87B	"	"	2.50	14.70	2.90	0.07
77	"	"	0.47	0.00	0.00	0.40
136	"	"	1.19	2.08	0.00	1.9
159	"	"	0.45	0.00	0.4	0.26

[1] Al-Ani, et al., EPA Report, June 1983.

[2] Choi, 1983.

[3] Table 1, Appendix A, from this document.

Figures 31 and 32 show high removals can be expected with it and it is less expensive than if a higher dosage is used.

Examination of data in Table A-1 for removals of total coliform bacteria as affected by polymer dosage, indicates similar results as obtained for percent removals of turbidity and *Giardia* cysts. Dosage removal data were obtained also using the polymer Magnifloc 573C. These results are not reviewed because they were almost identical to the results obtained using the polymer Magnifloc 572C.

Sequence of Coagulant Addition

In coagulation practice, when two stage rapid mix is used, it is common to add alum and then polymer. Addition of polymer first is not practiced. When only one rapid mix basin is used both alum and polymer must be added simultaneously. Whether the sequence of coagulant addition results in different turbidity removal efficiencies was investigated briefly. Experiments were conducted at two temperatures, 7°C and 18°C, using water having turbidity <1 NTU.

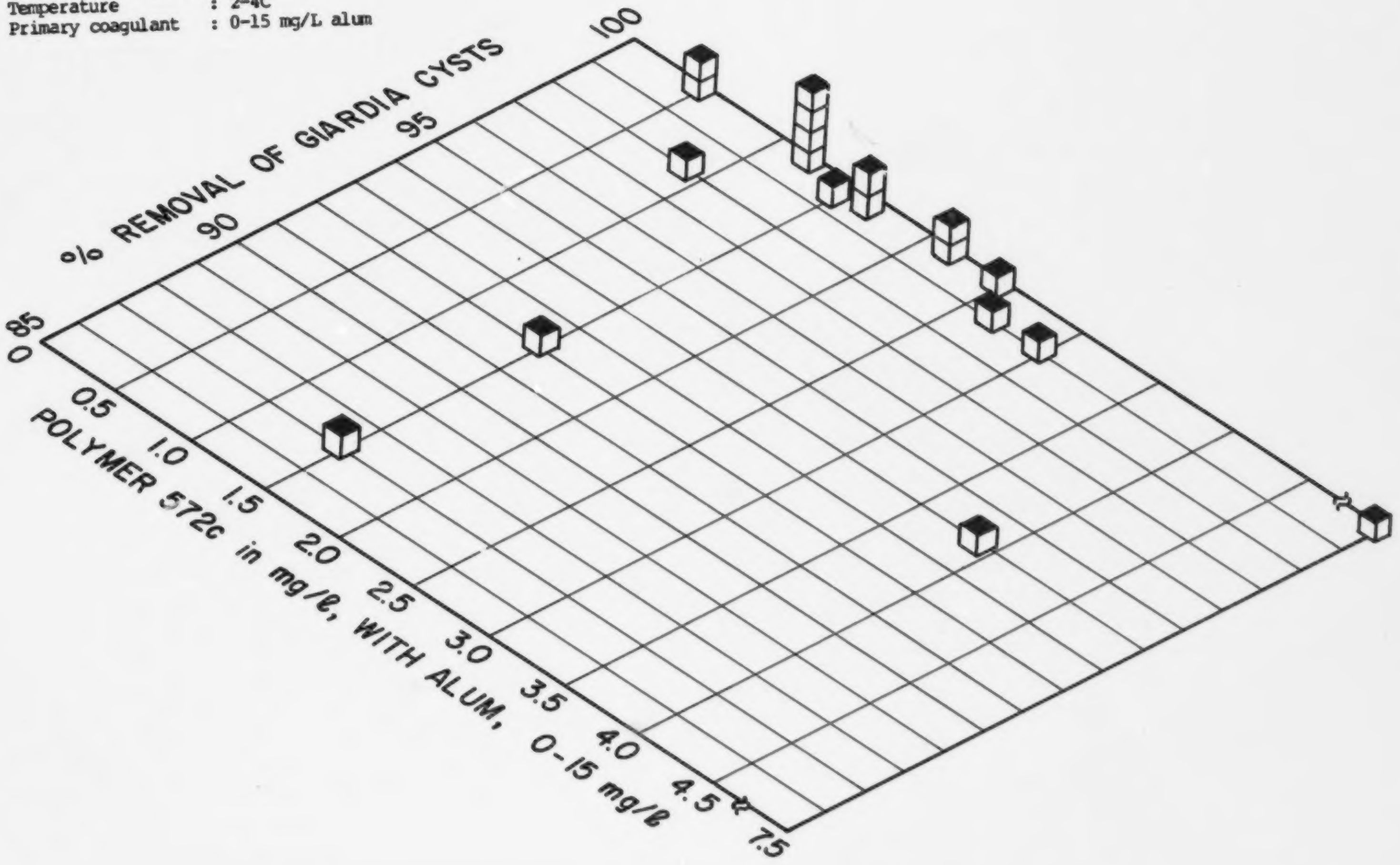
Appendix G shows results of the experiments, plotted as filter effluent turbidity monitored against elapsed run time. Figure G-1, for results of tests at 7°C shows that there is little difference whether both alum and cationic polymer are added simultaneously in one rapid mix basin, or if alum is added to a first basin, followed by cationic polymer in the second basin; effluent turbidity is about 0.1 to 0.15 for both. If cationic polymer is added first, however, the effluent turbidity is appreciably higher, e.g. about 0.25 NTU.

Figure G-2, for results of tests at 18°C, shows effluent turbidity is about the same for all three sequences of coagulant addition, but that this time turbidities are slightly higher if alum is followed by cationic polymer. But simultaneous addition of both gives turbidity levels of about 0.05 NTU.

Mode of Filtration

Table 13 shows results of test runs comparing "in-line" filtration with "direct" filtration. The chemical dosages were "optimum" with respect to turbidity removal for the "in-line" filtration mode. The results show that both modes of filtration gave about the same effluent turbidities and about the same headlosses in the filter columns. Figure 33 illustrates these results in graphical format for Test Runs 148 and 149. Figure G-3, Appendix G, shows the plots for Runs 146 and 147. Logsdon (1983) reported on the use of "direct" filtration to treat low turbidity raw of Lake Superior. The turbidity was reduced to 0.05 NTU with influent turbidity <1 NTU.

These data show that the same filter effluent turbidity was produced whether "in-line" or "direct" filtration was used. Therefore the "in-line" filtration mode was used for this research.



Test Conditions

Run number(s) : 19 test runs
Raw water turbidity : 0.36-2.5 NTU
Temperature : 2-4C
Primary coagulant : 0-15 mg/L alum

Figure 32. Histogram of Giardia cysts percent removal and dosage of Magnifloc 572C as coagulant aid using laboratory-scale rapid rate pilot plant. Each block represents on measurement set.

Table 13. "In-line" filtration versus direct filtration data.

Run No.	Influent Turbidity (NTU)	Filtration Mode	Alum[1]		Polymer[2]		Flocculation Basin[3]				Time[4] (hour)	Head Loss (cm Hg)	Effluent Turbidity (NTU)
			(mg/L)	GT	(mg/L)	GT	G	T	G	T			
146	0.89	In-line	9.32	64824	0.351	64824	0	0	0	0	2.33	10.6	0.09
147	0.89	Direct	9.32	64824	0.351	64824	37.0	1106	36.8	1106	3.00	11.5	0.10
148	1.06	In-line	4.12	66984	0.62	66984	0	0	0	0	4.00	11.5	0.09
149	1.06	Direct	4.12	68542	0.65	68592	37.0	1171	36.8	1171	4.00	12.7	0.10

[1] Alum as $Al_2(SO_4)_3 \cdot 14H_2O$

[2] Polymer Magnifloc 572C

[3] $G = (P/uV)^{1/2}$

P = the power dissipated (lb ft/sec)
u = absoulte viscosity ($lb\text{-}sec/ft^2$)
V = the volume to which P is applied (ft^3)
G = velocity gradient (sec^{-1})
T = detention time (sec) = V/Q
Q = the flow rate (ft^3/sec)

[4] Time when reading taken.

Test Conditions

Run number(s) : 148 "in-line", 149 "direct"
Raw water turbidity : 1.06 NTU
Temperature : 4C
Primary coagulant : Run 148 and Run 149, 4.1 mg/L alum

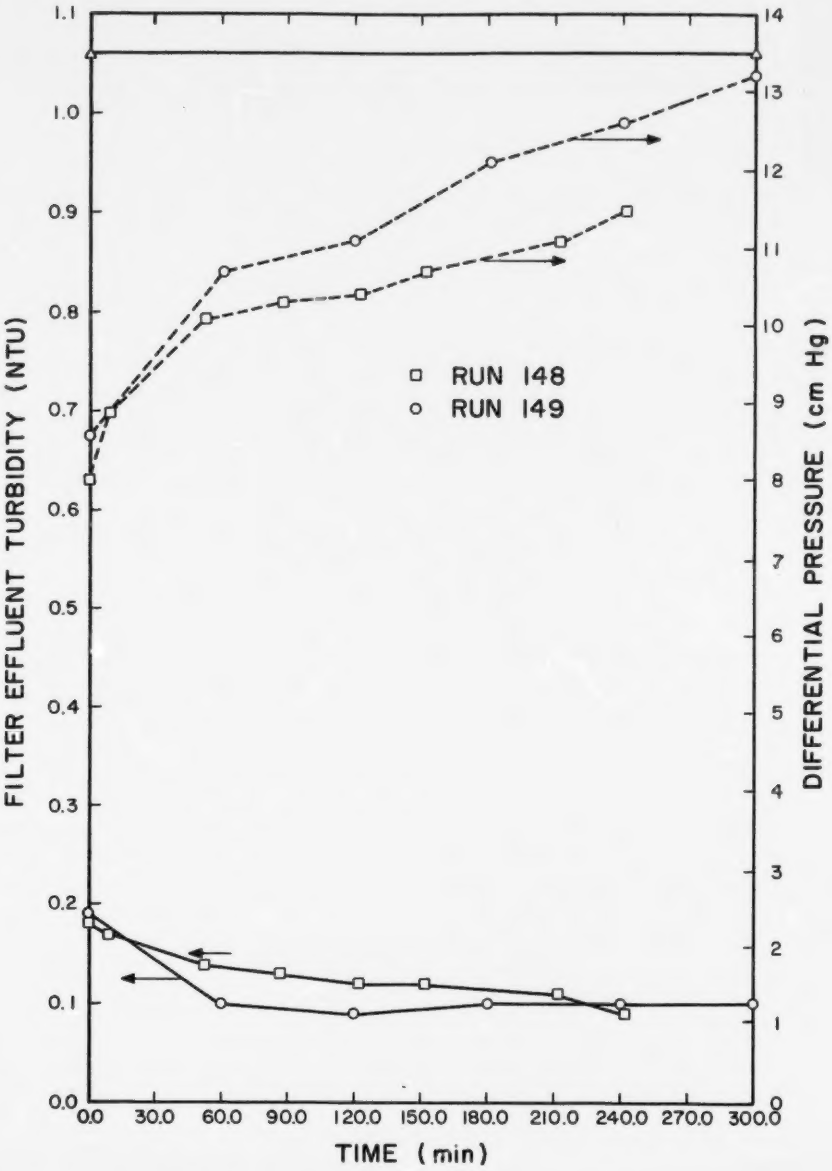


Figure 33. Comparison of turbidity and headless, for "in-line" and "direct" filtration. Laboratory-scale pilot plant using artificial low turbidity water from Horsetooth Reservoir, and dual media Fort Collins sand.

Comparison of Single and Dual Media

Table 14 summarizes results of test runs which compared the effluent turbidities and headloss for single media filter of 76 cm sand with a dual media filter of 30 cm sand, 45 cm anthracite. Three comparisons were made using the same tank of water for each pair. Figures G-4, G-5, G-6 are plots of the results showing turbidity and headloss vs time for each comparison pair.

The first comparison, seen in Figure G-4, was for the no chemical pretreatment condition. Results show comparable effluent turbidities but higher headloss for the single media, e.g. 6.8 cm Hg for single media vs 4.0 cm Hg for dual after 50 minutes of operation. The second comparison, seen in Figure G-5, was conducted using alum and polymer at optimum dosage with respect to turbidity removal. Effluent turbidities were 0.04 NTU for both, and again headloss was higher for the single media. The third comparison used only one coagulant, the polymer 573C. Effluent turbidity was 1.7 NTU for sand and 2.4 NTU for dual media. Headloss as 8.0 cm Hg for sand after 210 minutes of operation, versus 3.7 cm Hg for dual media as shown in Figure G-6.

Based upon these results, and due to the wide spread use of dual media, the latter was used in this research. Although the effectiveness for each was the same with respect to turbidity removal, the appreciably higher headloss experienced using sand as a single media confirms the use of dual media in practice.

Filtration Rate

Table 15 shows the effect of using different filtration rates, for two dual media filters, on removals of turbidity, standard plate count bacteria, total coliform bacteria, and Giardia cysts. Figures 34 and 35 are plots of these data for Fort Collins sand and for Loveland sand, respectively. Both figures show, for the four parameters plotted, that filtration rate has virtually no effect on percent removals in the range 8.1 cm/min (2 gpm/ft^2) to 24 cm/min (5 gpm/ft^2). As noted removals of total coliform bacteria were greater than 99 percent for all hydraulic loading rates while removals of standard plate count bacteria were greater than 96 percent and removals of Giardia cysts exceeded 95 percent except at the highest filration rate used. Further there is little effect up to 32.6 cm/min (8 gpm/ft^2) except a noticeable decline occurs in percent turbidity removal for filtration velocity for 40.8 cm/min, as shown in Figure 35. At the filtration rate of 40.8 cm/min (10 gpm/ft^2) the declines in percent removals are noticeable for total coliform bacteria and standard plate count bacteria, and markedly noticeable for Giardia cysts and turbidity.

Temperature

Table 16 shows effluent turbidity and percent removals of standard plate count bacteria and total coliform bacteria for temperatures of 5°C and 18°C, with all other conditions the same for each paired comparison. Comparison of

Table 14. Comparison of effluent and headloss for single and dual media using laboratory scale rapid rate filtration pilot plant.

Run No.	Influent 1/ Turbidity (NTU)	Media 2/	Alum Dosage (mg/L)	Polymer Dosage 3/ (mg/L)	Time 4/ (min)	Headloss (cm Hg)	Effluent Turbidity (NTU)
76	0.5HDE	sand	0	0	50	6.8	0.4
77	0.5HDE	dual	0	0	50	4.0	0.4
71	1.0HDE	sand	15.5	1.3	210	10.9	0.04
72	1.0HDE	dual	15.5	1.3	210	5.7	0.04
98	2.4HDE	sand	0	8.8	210	8.0	1.7
99	2.4HDE	dual	0	7.5	210	3.7	2.4

1/ HDE is water obtained from Horsetooth Reservoir, filtered by Diatomaceous Earth to give low turbidity, e.g. 0.2 to 0.6 NTU.

2/ Sand was obtained from Loveland Treatment Plant at Big Thompson Canyon. Bed depth was 76cm. Dual means the bed was comprised of 30 cm sand from Loveland and 45 cm anthracite having trade name Philterkol Special (R) No.1(produced by Reading Anthracite Coal Company. Pottsville, PA. 17901).

3/ Polymer used was Magnifloc 573C (R)

4/ Time is elapsed time for corresponding headloss and effluent turbidity obtained from plots of data.

Table 15. Effect of filtration rate on removal of turbidity, standard plate count bacteria, total coliform bacteria, and Giardia cysts for dual media using two sources of sand[1]. All other conditions were approximately the same. Laboratory-scale rapid rate filtration pilot plant was used. Coagulant dosages were those in which minimum effluent turbidity was attained.

Run No.	Filtration rate (cm/min)	Media	Chemical used[2]	Turbidity			Total Coliform Bacteria			Standard Plate count Bacteria		
				Raw[3] water (NTU)	Filter Effluent (NTU)	Percent removal	Influent (No./100mL)	Effluent (No./100mL)	Percent removal	Influent (No./mL)	Effluent (No./mL)	Percent removal
114	7.8	Anth/ F.C. sand	23.2/1.2	1.13	0.10	91	695	<1	>99.9	27,500	880	96.8
113	20.6		18.5/1.0	1.13	0.12	89	695	1	99.9	27,500	30,000	-0.0
112	32.6		18.5/1.0	1.13	0.3	73	1,500	8	99.5	30,000	410	98.6
111	41.0		18.6/1.0	1.13	0.5	57	1,500	15	99.0	30,000	1,300	95.7
118	9.4	Anth/ Lov. sand	23.6/1.4	1.24	0.18	81	790	5	99.4	9,000	140	98.4
116	21.0		23.3/3.0	1.28	0.23	82	1,400	<1	99.9	12,500	20	99.8
117	32.3		37.3/1.6	1.24	1.05	15	790	3	99.6	9,000	2,000	77.8
115	40.4		34.3/1.6	1.28	0.27	79	1,400	<1	99.9	12,500	40	99.7

[1] Anthracite used for both media was Philterkal (R), d_{10} = 0.9 mm, UC = 1.45. Fort Collins sand, d_{10} = 0.5 mm, UC = 1.4, Fort Collins sand was the term used to designate sand obtained from Fort Collins Treatment Plant No. 2. Loveland sand, d_{10} = 0.43 mm, UC = 1.5. Loveland sand is the term used to designate sand obtained from Loveland Big Thompson Canyon Water Treatment Plant.

[2] Expressed as mg/L alum as $Al_2(SO_4)_3$ $14H_2O$ and mg/L Magnifloc 572 Polymer. Cache La Poudre River water with temperature of 3°C and turbidity 0.6 NTU.

[3] Turbidity changed from 0.6 NTU to 1.13 NTU after contaminate of raw sewage and dog feces were added to milk cooler. Water was obtained from Cache La Poudre River in April 1983.

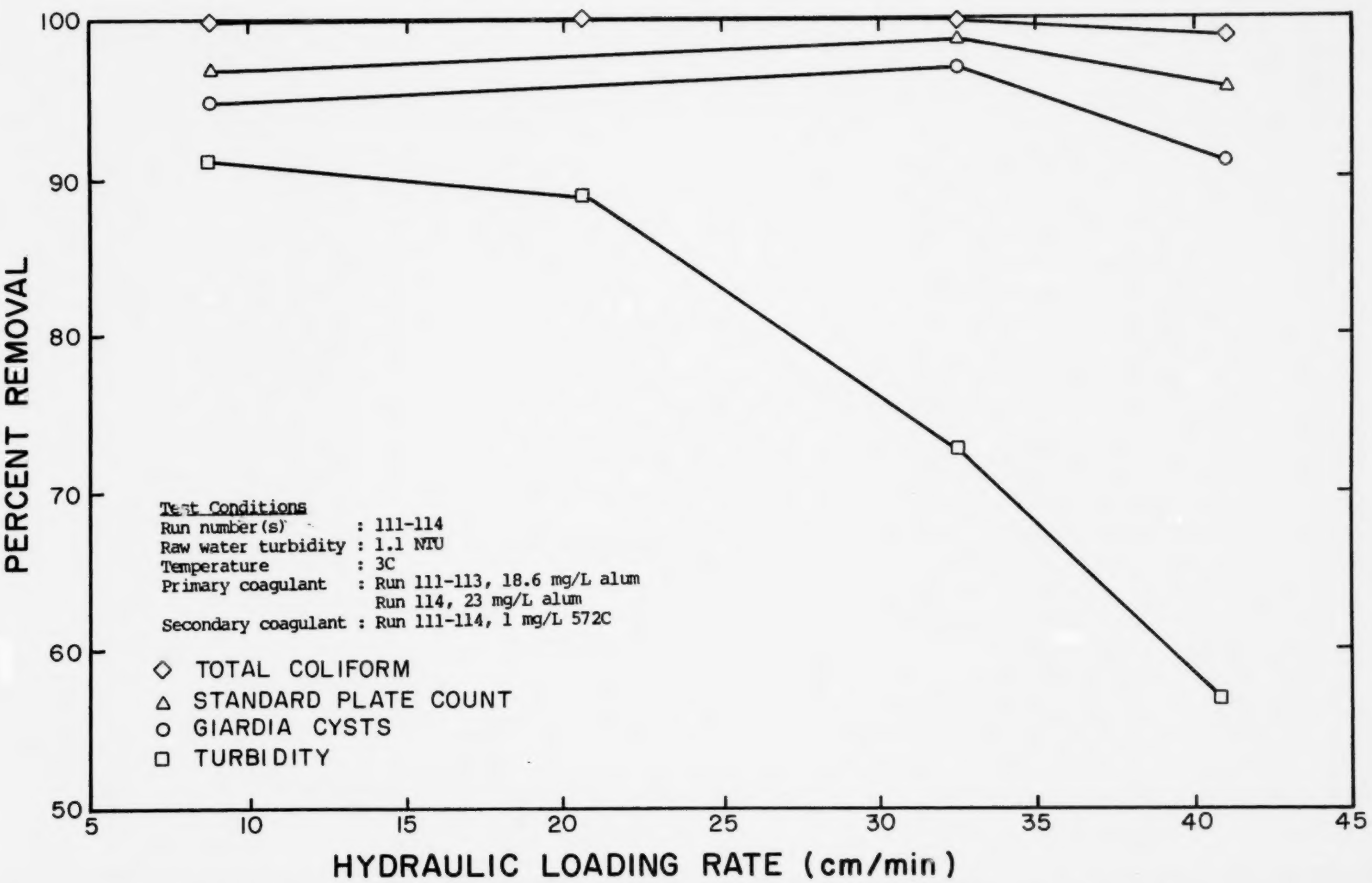


Figure 34. Effect of hydraulic loading rate on percent removal of turbidity, standard plate count bacteria, total coliform bacteria, and *Giardia* cysts, using laboratory-scale rapid rate filtration pilot plant packed with dual media with Fort Collins sand.

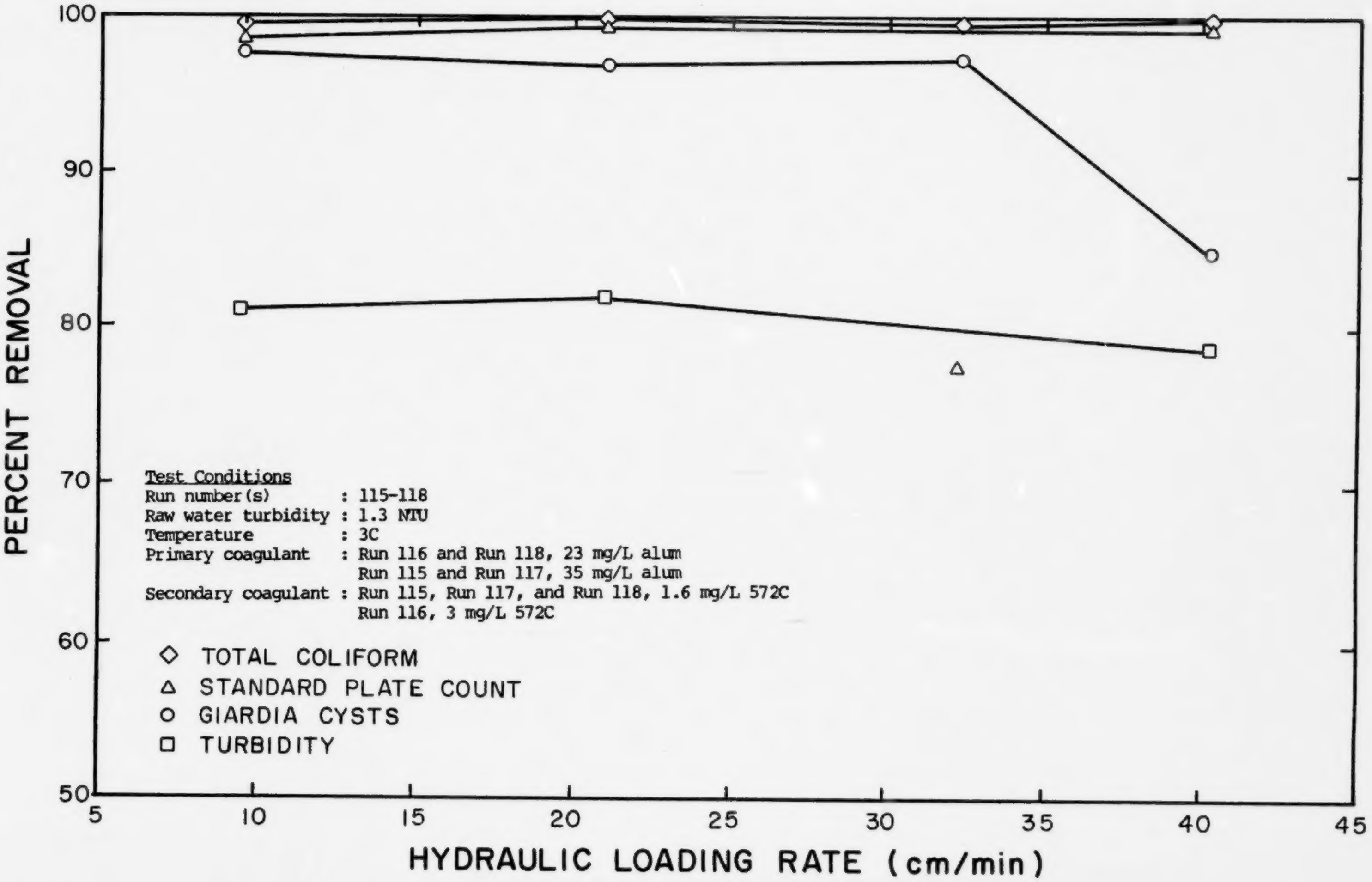


Figure 35. Effect of hydraulic loading rate on percent removals of turbidity, standard plate count bacteria, total coliform bacteria, and *Giardia* cysts using laboratory-scale rapid rate filtration pilot plant packed with dual media with Loveland sand.

Table 16. Effect of temperature on removal of turbidity, standard plate count bacteria, total coliform bacteria, for different chemical dosages.

Run No.	Influent Turbidity (NTU)	Chemical Species	Dosages (mg/L)	Temp. (°C)	Effluent Turbidity (NTU) 1/	% Removal Standard Plate count	% Removal Total Coliform
159	0.45	572C	0.42	5	0.3	90.0	97.0
151	0.45	572C	0.42	18	0.2	-77	86.6
160	0.45	Alum/572C 2/	4.31/1.85	5	0.10	95.89	99.5
152	0.45	Alum/572C 2/	4.31/1.85	18	0.08	77.6	>99
158	0.45	Alum/572C	5.47/0.48	5	0.2	93.7	99.7
154	0.45	Alum/572C	5.47/0.48	18	0.15	82.6	93.1
157	0.45	572C/Alum	1.00/9.0	5	0.32	91.5	99.6
155	0.45	572C/Alum	1.00/9.0	18	0.08	93.2	99.8

1/ Turbidity values was obtained from Figures E-7 to E-10, Appendix E at 90 minutes of filtration run time.

2/ Alum and polymer were added simultaneously using one rapid mix basin each pair of data indicates no discernable difference due to the effect of temperature. This is corroborated further by plots of turbidity versus time for the two temperatures, shown in Figures G-7 to G-10, Appendix G. Figure G-8 and G-9 show no differences in the plots of effluent turbidity versus time at 5°C and 18°C. The two plots are different in Figure G-10, where polymer was added to the first rapid mix basin and alum was added to the second, for each of the two tests at 5°C and 18°C. This result is not consistent with the others (where alum was added first); an explanation is not offered. All tests were done at coagulant dosage which gave minimum effluent turbidities.

Those same plots, e.g. Figures G-7 to G-10, show an appreciable difference in the headloss versus time curves between 5°C and 18°C. The initial headloss at time zero for the 18°C water temperature was nominally 7 cm of Hg, and about 9.5 cm Hg for the 5°C tests for each of the four pairs of headloss versus time curves. Further, the rate of headloss increase was the same for both temperatures for three of the four pairs. The difference is due to the effect of temperature on dynamic viscosity of water. This can be seen by examining the ratio of initial headlosses for 5°C and 18°C, respectively, in Figure G-8, e.g. 10.2 cm Hg/7.0 cm Hg (which equals 1.45), and comparing with the ratio of dynamic viscosities of water at the two temperatures, which is 1.46 (using Darcy's law as the basis). This close comparison establishes that the headloss difference was due to the effect of temperature of the viscosity of water.

The effect of temperature on removals cannot be discerned from these few tests. But if a temperature effect does exist these data indicate that it may not be strong within the range 5°C to 18°C.

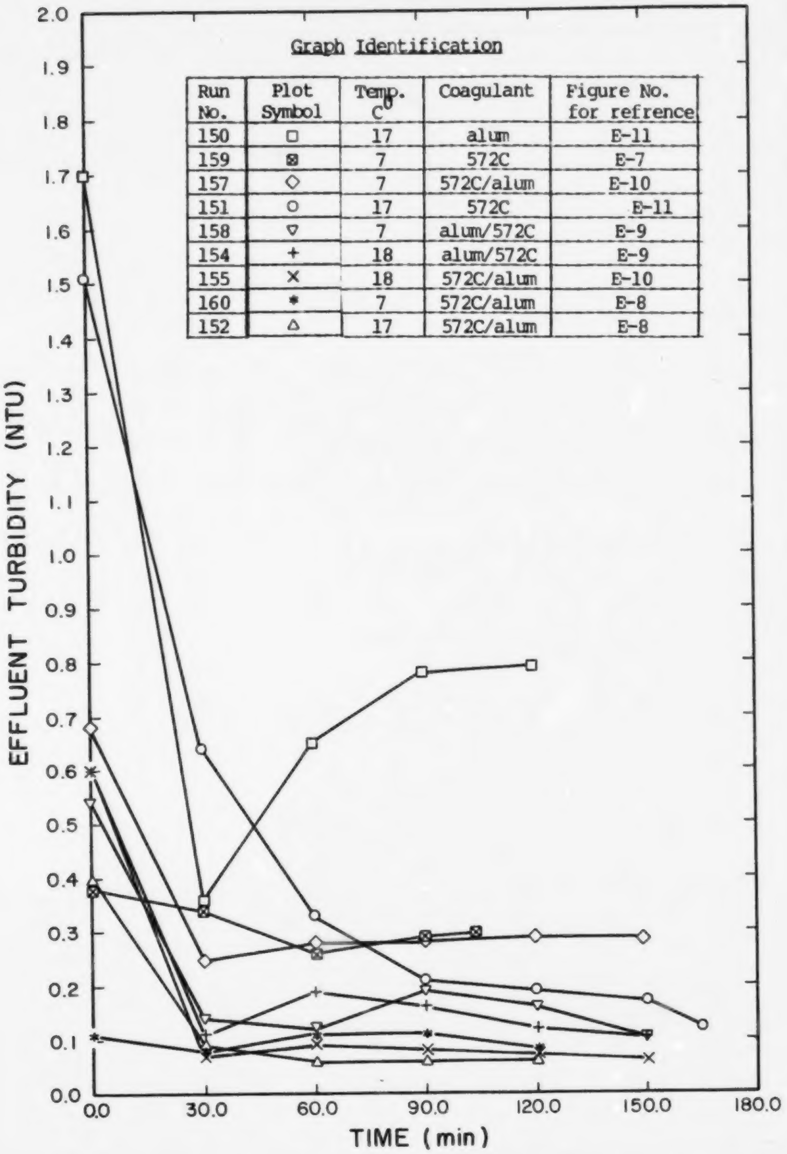
Run Time

Of widespread interest is the effectiveness of rapid rate filtration with respect to elapsed time after backwash, called "run time" here. This question was of interest with respect to removals of turbidity and other parameters measured, including *Giardia* cysts. It was of interest also with respect to sampling protocol, since it was desired to obtain samples after the run had "stabilized."

Figure 36 and 37 show the effect of run time on effluent turbidity, and headloss, respectively using water having turbidity less than 1 NTU. Figure 36 shows that effluent turbidity was about constant after 30 minutes of run time. The rapid decline between 0-30 minutes was due to the fact that the detention time in the tubes, pipes, and filter was nominally about 30 minutes (it was 30 minutes from the coagulant box to the filter effluent for a flow fo 450 mL/min to a 5 cm filter). This means that the system is essentially "steady state" after 30 minutes and that representative sampling can be done after this time. Complete conditions associated with the test runs in Figure 36 are described in Figures G-7 to G-11.

Test Conditions
Run number(s) : 150-152, 154-160
Raw water turbidity : 0.45 NTU
Temperature : 18C
Primary coagulant : 0-9 mg/L alum

Secondary coagulant : 0.42-1.8 mg/L 572C



Graph Identification

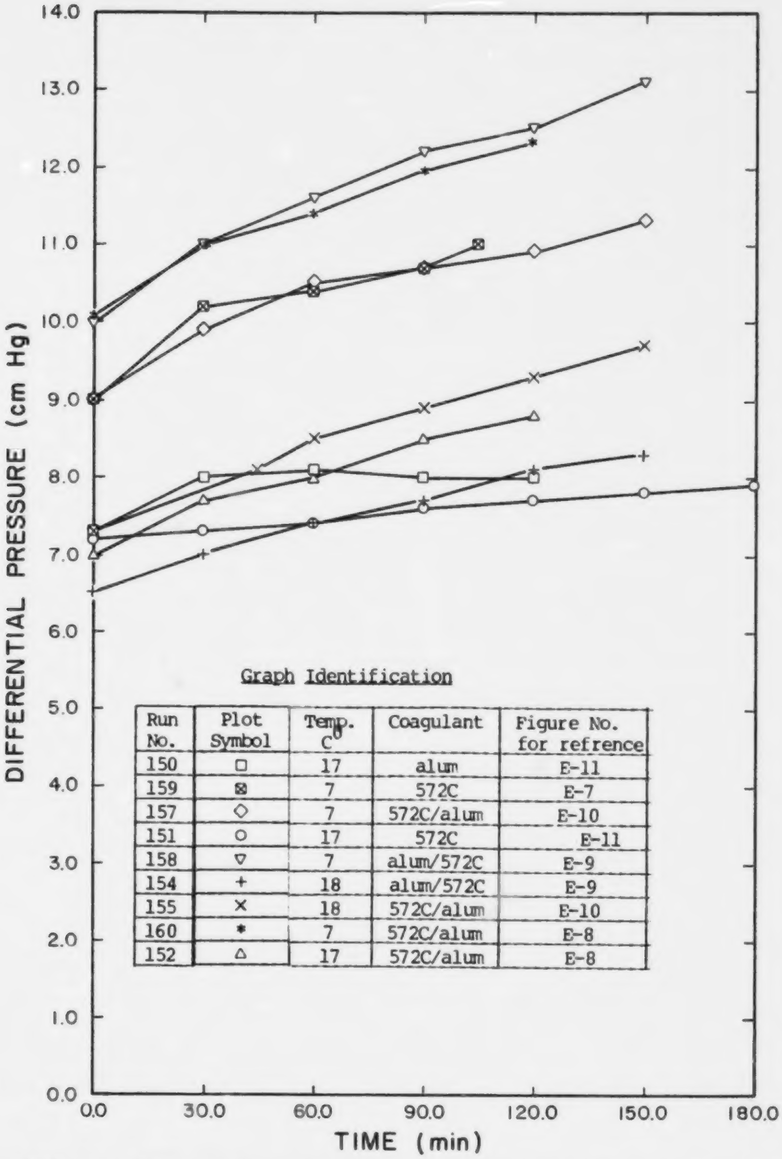
Run No.	Plot Symbol	Temp. C^0	Coagulant	Figure No. for refrence
150	□	17	alum	E-11
159	⊠	7	572C	E-7
157	◇	7	572C/alum	E-10
151	○	17	572C	E-11
158	▽	7	alum/572C	E-9
154	+	18	alum/572C	E-9
155	×	18	572C/alum	E-10
160	*	7	572C/alum	E-8
152	△	17	572C/alum	E-8

Figure 36. Effect of run time on turbidity reduction for different temperatures and coagulants. Figures H-7 to H-11, Appendix H describe complete conditions.

Test Conditions

Run number(s) : 150-152, 154-160
Raw water turbidity : 0.45 NTU
Temperature : 18C
Primary coagulant : 0-9 mg/L alum

Secondary coagulant : 0.42-1.8 mg/L 572C



Graph Identification

Run No.	Plot Symbol	Temp. C°	Coagulant	Figure No. for refrence
150	□	17	alum	E-11
159	⊠	7	572C	E-7
157	◇	7	572C/alum	E-10
151	○	17	572C	E-11
158	▽	7	alum/572C	E-9
154	+	18	alum/572C	E-9
155	×	18	572C/alum	E-10
160	*	7	572C/alum	E-8
152	△	17	572C/alum	E-8

Figure 37. Effect of run time on headless for different temperatures and coagulants. Figures H-7 to H-11, Appendix H, describe complete conditions.

Figure 37 shows headloss increase with time for the same test runs used to plot Figure 36. As explained in the section on temperature effects the differences between the initial headloss values is due to temperature differences. The rate of headloss increase is due to the differences in coagulants, or coagulation conditions. For alum/572C the rate of headloss increase was about 0.5 cm Hg/hr. For 24 hour run this would be 12 cm Hg, which is 1.6 meters of water. If the allowable headloss is 3 meters, the run time could be about 45 hours, assuming turbidity breakthrough does not occur first and assuming the headloss increase is linear, and not exponential. The longest run time in these experiments was about 6 hours, during which turbidity was stable.

Table 17 shows removals of five parameters, turbidity, particles, total plate count bacteria, total coliform bacteria, and Giardia cysts, for sampling at 30 minutes run time and at 90 minutes. The table shows two categories of coagulant dosages, "optimum" and "nonoptimum." Removals are uniformly high for all parameters at optimum chemical dosages. But in relation to the question at hand, there is essentially no difference in percent removals at these two times. In practical terms it means there is little need to run filter to waste after the coagulants have become effective in interacting with the filter media. These conclusions do not mean that filter to waste is not advisable. After backwash the incoming coagulant water will mix with the backwash water and there could be a reduction in filter effectiveness during this period.

RELATIONSHIPS BETWEEN DEPENDENT VARIABLES

The most common indicator of water treatment effectiveness is finished water turbidity. It is common practice to use finished water turbidity as an operating parameter when raw water turbidity exceeds 1 NTU. For low turbidity waters, however, this parameter is monitored, but it is not used to control operation; the turbidity standard of 1 NTU is simply not exceeded. But since turbidity is easy to measure and to measure accurately, its use as an operating parameter for low turbidity water was examined. At the same time, other parameters were examined, such as particles, standard plate count bacteria, and total coliform bacteria. Of casual interest was to ascertain whether percent turbidity removal could be an effective surrogate measure for percent removals of any of the foregoing parameters. But the main quest was to determine whether percent removal of turbidity, or any of the other parameters, mentioned above could serve as an index of percent removal of Giardia cysts. It should be noted also that when using low turbidity mountain waters that levels of total coliform bacteria in mountain streams are very low, e.g. less than 100 per 100 mL (Psaris and Hendricks, 1982). This means that coliform bacteria may not be an effective indicator of percent removal of any parameter if ambient concentrations of coliforms are used. Despite this possible practical limitation it was examined experimentally. Its use as an indicator of filtration would be nullified also if prechlorination is practiced.

Therefore, the test data obtained in this work, and reported in the foregoing sections, were plotted in terms of one parameter versus another,

Table 17. Effect of elapsed time after backwash on removal of Giardia cysts, particles, standard plate count bacteria, total coliform bacteria, for low turbidity, low temperature water at "optimum" and "non-optimum" coagulant dosages.[1]

Run No.	Water Source	Inffluent[2] Turbidity (NTU)	Coagulant[3] Dosages	Percent Removal									
				30 Minutes Run Time[4]					90 Minutes Run Time[4]				
				Turbidity	Particle Count	Standard Plate	Total Coliform	Giardia Cysts[5]	Turbidity	Partical Count	Standard Plate	Total Coliform	Giardia cysts[5]
85	HDE	2.2	Optimum	95.9	99.3	96.9	>99.9	>99.9	94.6	75.9	95.0	98.6	99.8
86	HDE	2.2	Optimum	95.2	99.5	99.0	99.8	99.9	97.6	99.8	99.0	96.7	>99.9
87	HDE	2.2	Optimum	96.0	91.4	99.4	99.5	>99.9	97.2	>99.9	99.7	99.7	>99.9
88	HDE	2.2	Optimum	94.2	99.7	95.9	99.9	99.9	76.8	56.7	92.6	99.9	99.8
89	HDE	2.2	Optimum	96.8	>99.9	94.1	98.8	>99.9	97.1	92.7	98.9	97.8	99.9
90	HDE	2.2	Optimum	95.5	99.9	-[6]	>99.9	>99.9	96.4	99.9	-[6]	>99.9	>99.9
91	HDE	2.2	Optimum	95.0	99.9	72.4	99.9	>99.9	96.7	99.9	86.4	94.8	99.9
101	CLP	4.8	Optimum	87.5	99.7	97.9	99.9	99.4	68.9	99.8	>99.9	99.9	99.7
102	CLP	6.2	Nonoptimum	76.5	27.1	00.0	00.0	98.6	41.9	34.7	00.0	00.0	95.4
104	CLP	1.1	Nonoptimum	16.7	98.8	50.4	-24.4	97.4	82.4	98.6	99.5	79.8	98.7
107	CLP	0.7	Nonoptimum	60.3	95.4	96.7	90.0	99.7	92.7	95.4	96.7	90.0	99.9

1/ Abstracted from Table A-1 and Table A-2, Appendix A.

2/ Turbidity level after contaminate of raw sewage and dog feces were added to milk cooler, turbidity level prior to these additons ranged from .45 to.70 NTU.

3/ Coagulants used for test runs 85,86,87 were alum and 572C. For other test run the coagulants used were alum and 572C. The term "optimum" coagulant dosage means any dosage resulting lowest effluent turbidity levels.

4/ Time elapsed after back wash when sampling was initiated. Sampling duration was about 30 minutes for Giardia cysts, and only long enough to fill the sample bottle for grab sample.

5/ Percent recovery is reported as detection limites where zero cysts were recovered, and are indicated by the "greater than" symbol. The calculation of detection limit is showen in Appendix G.

6/ No sample taken.

e.g. percent removals of turbidity versus Giardia cysts, total coliform bacteria versus Giardia cysts, turbidity versus total coliform bacteria, and turbidity versus standard plate count bacteria. These relationships were plotted by histograms and then were examined further by means of statistical tests. All relationships discussed in this section have used data obtained from operation of the laboratory-scale pilot plant.

Surrogate Indicators for Giardia Cyst Removal

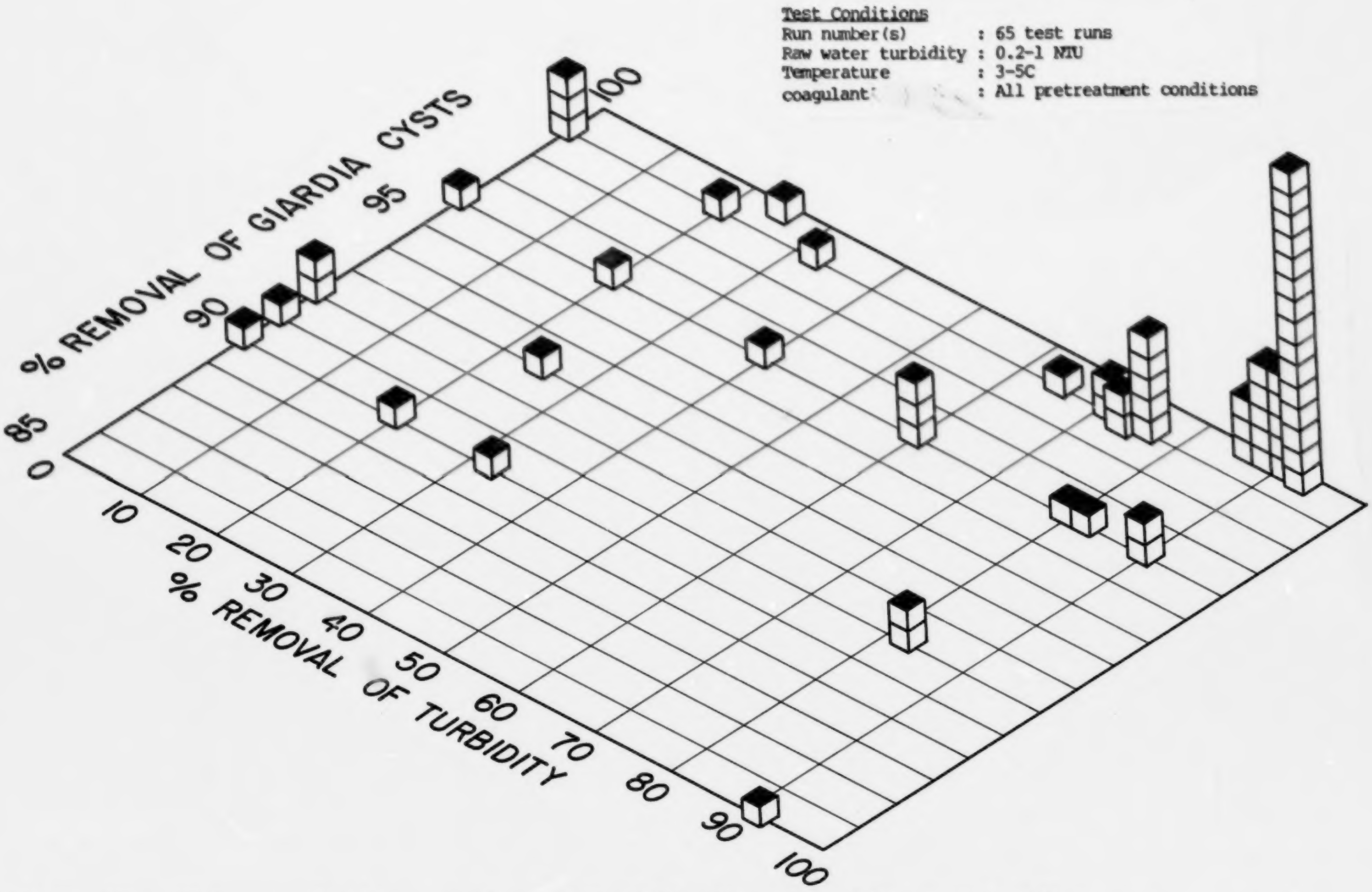
Detection and measurement of Giardia cysts requires the services of a skilled parasitologist, knowledgeable of techniques for concentration, and having continuing practice in identification of the organism. Thus it is desirable that a surrogate be found to substitute for routine measurement of Giardia cysts which can be incorporated into water treatment practice. Therefore, a surrogate for percent removal of Giardia cysts, is another quest of this research. Several were investigated, including turbidity, particles, standard plate count bacteria, and total coliform bacteria. Histogram plots were developed for two of these possible surrogates, turbidity and total coliform bacteria, using data from Table A-1 and Table A-2. These were selected for examination because both are easy to measure and could be used in evaluation of performance of the filtration process.

Turbidity—

Figure 38 is a histogram showing percent removal of Giardia cysts and corresponding values of percent removal of turbidity. Figure G-12 is a plot of observations, used partially to construct Figure 38, but with all data shown. Figure 38 shows that if turbidity removal is high, then removal of Giardia cysts will be high also. To be more specific, the plot shows 44 observations when turbidity removal is greater than 70 percent. Of these, 37 have removals of Giardia cysts of 99 percent or more. In other words, if turbidity removal exceeds 70 percent the probability is 0.85 (e.g. 37/44) that removal of Giardia cysts will be equal to or exceed 99 percent.

Figure 39 is a "probability of occurrence" plot, explained in Appendix F. It was obtained by ordering the data shown in Figure G-12 for statistical analysis, as explained in Appendix F. This plot shows that if percent removal of turbidity is at a given level, say 70 percent, then there is an 0.85 probability that removal of Giardia cysts will exceed 95 percent. This is a result only slightly different than obtained using the histogram, Figure 38. The histogram is a visual intuitive representation of the same information. Figure 38 is more quantitative.

While Figure 39 is useful in understanding the relationships shown (e.g. percent turbidity removal and probability of having a certain percent removal of Giardia cysts) it probably is not accurate for the lower percent removals of turbidity. This is due to the fact that data were not abundant in this range. In other words, while the plot generated represents the "sample," it may not necessarily represent accurately the "population," at least not in the lower ranges of percent removal of turbidity.



Test Conditions
Run number(s) : 65 test runs
Raw water turbidity : 0.2-1 NTU
Temperature : 3-5C
coagulant : All pretreatment conditions

Figure 38. Histogram showing percent removal of Giardia cysts with corresponding percent removal of turbidity. Each block represents one measurement set. Data points are for water having turbidity of less than 1 NTU, and temperature 3-5°C.

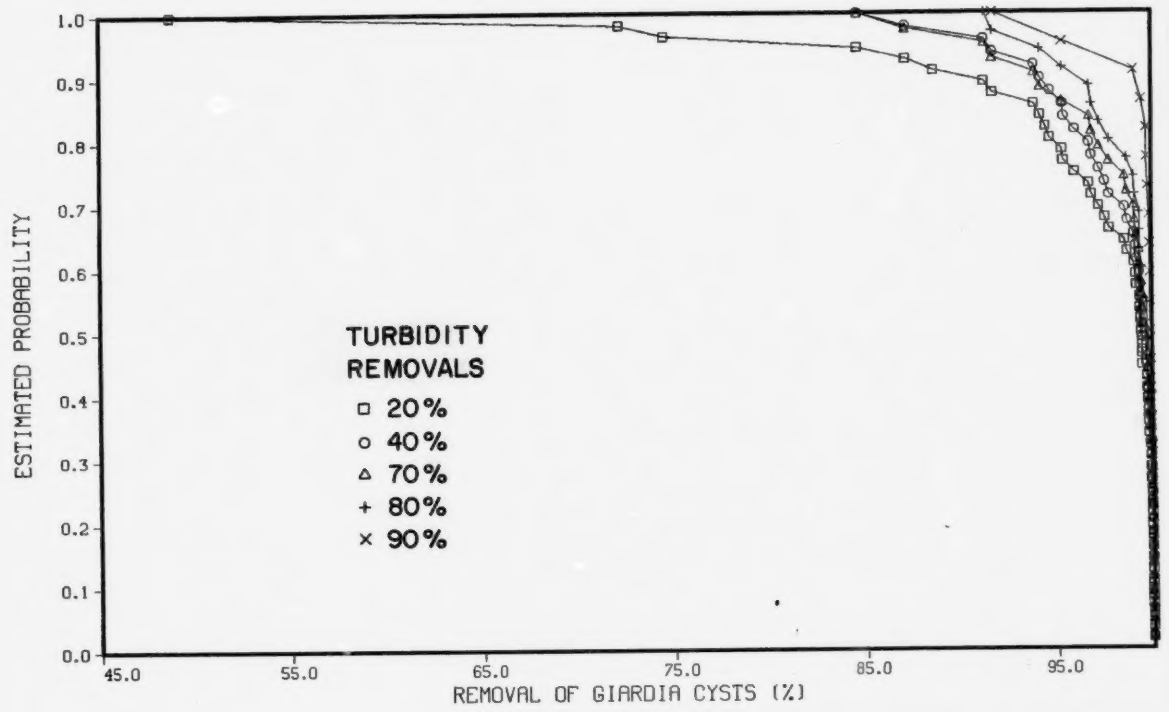


Figure 39. Probability of a given percent removal of *Giardia* cysts for specified percent removals of turbidity. Data obtained from Table A-1 and Table A-2 plotted in Figure H-12.

A statistical test between the two variables (percent removal of *Giardia* cysts and percent removal of turbidity) showed that a positive association exists, with 99.5 percent confidence level, as tested by the student t-distribution. In other words, it is virtually certain that a functional relationship exists betweeen the two variables.

Total Coliform Bacteria--

Figure 40 is another histogram showing percent removal of *Giardia* cysts and corresponding values of percent removal of total coliform bacteria showing all observations available. Figure 40 shows that if percent removal of total coliform bacteria is high, then high percent removals of *Giardia* cysts can be expected. Counting the observations in the range of 90 to 100 percent removal of total coliform bacteria, there is 0.70 probability that removal of *Giardia* cysts will be 99 percent or greater, and 0.85 probability that *Giardia* removal will exceed 96 percent. Figure 41 is another probability of occurrence plot for the sample of data shown in Figure G-13. By comparison, it shows that if percent removal of total coliform bacteria is 98 percent, then there is 0.82 probability that percent removal of *Giardia* cysts is 96 percent or greater, which compares closely with the same calculation using the histogram data.

A statistical test between the two variables (percent removal of *Giardia* cysts and percent removal of total coliform bacteria) shows that a positive association exists, with 99.5 percent confidence level, as tested by the student t-distribution. Again, this says that it is virtually certain that a functional relationship exists between the two variables.

Standard Plate Count Bacteria--

Grab samples obtained for bacteria sampling were analyzed for standard plate count bacteria as well as total coliform bacteria. Relationhips obtained between percent removals of standard plate count bacteria and percent removals of *Giardia* cysts were virtually the same as obtained using percent removal of total coliform bacteria. Figure G-14 shows percent removals of *Giardia* cysts plotted against percent removals of standard plate count bacteria. Both the plot and the student t-distribution statistics are essentially the same as obtained for total coliform bacteria vs *Giardia* cyst plots in the preceding paragraphs. Figure G-15 is a probability of occurrence plot for the data shown in Figure G-14. This plot is similar to Figure 41 where total coliform bacteria is used as indicator.

Particles--

Particle counting of grab samples of raw water and finished water was done for 12 test runs out of a total of 178. Percent removals of particles were not plotted against percent removals of *Giardia* cysts. But inspection of Table A-1 and Table A-2 shows that the correlation is not high when compared with the other surrogates.

Turbidity Removal As A Surrogate

As noted previously, turbidity is easy to measure and it can be accurate as well. It is also used routinely in water treatment practice. The

Test Conditions

Run number(s) : 51 test runs
Raw water turbidity : 0.2-3 NTU
Temperature : 3-5C
coagulant : All pretreatment conditions

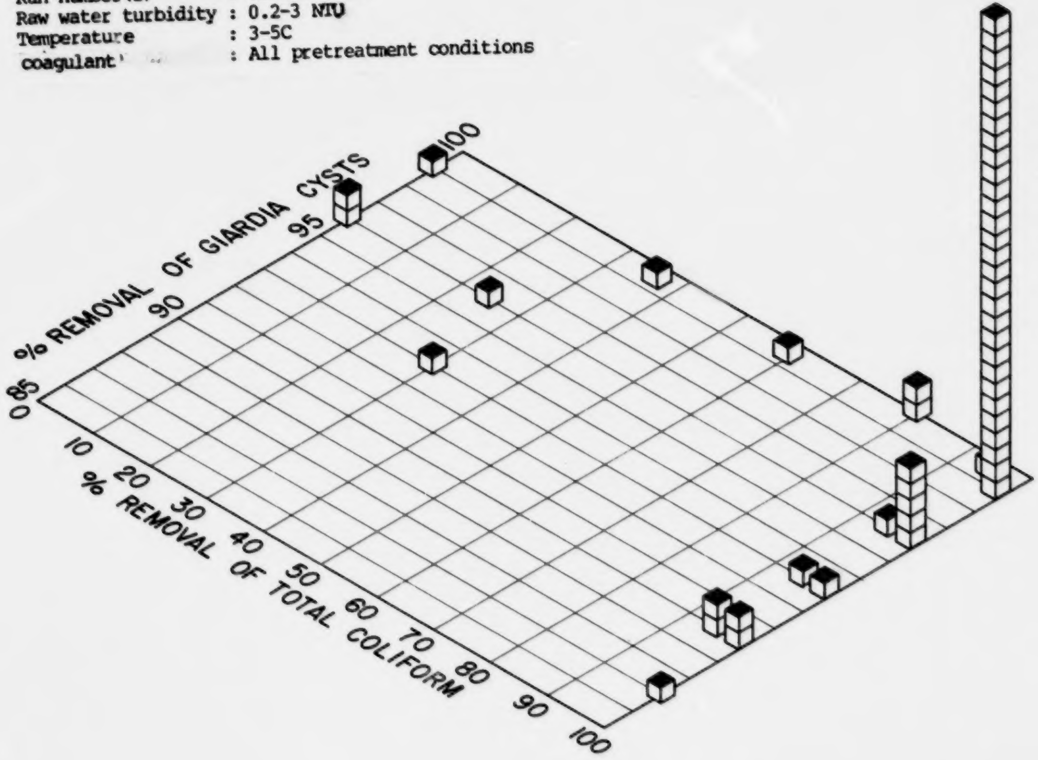


Figure 40. Histogram showing percent removal of Giardia cysts with corresponding percent removal of total coliform bacteria. Each block represents one measurement set.

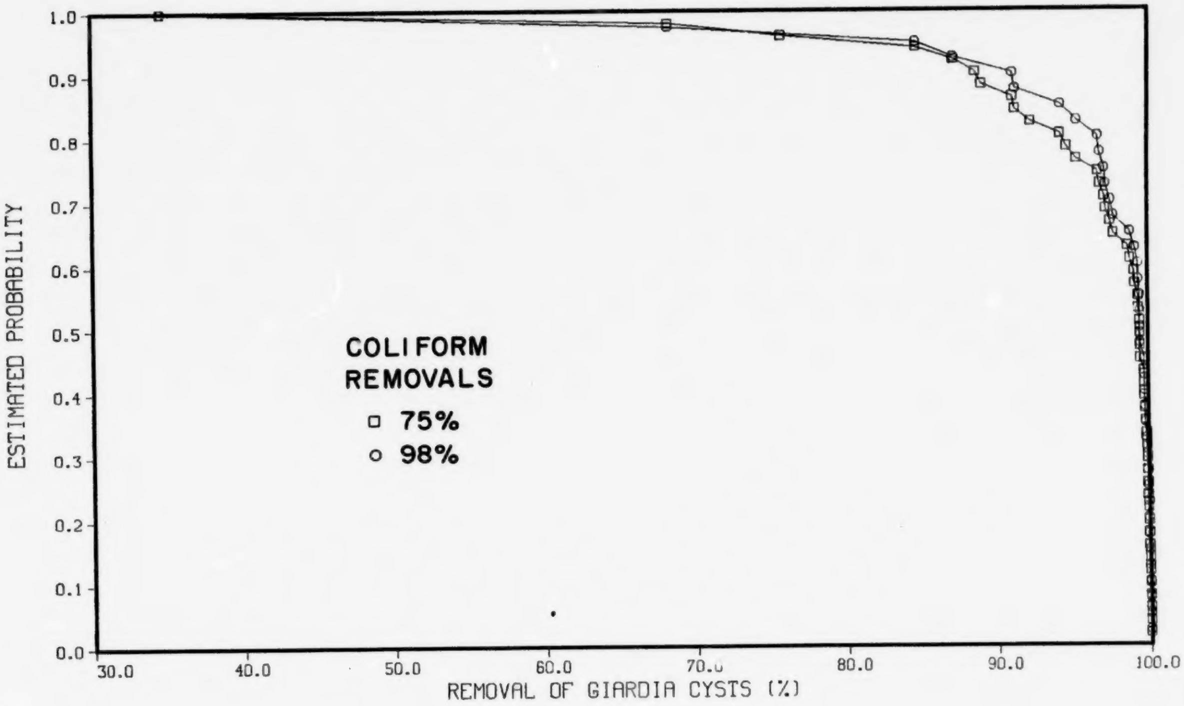


Figure 41. Probability of a given percent removal of *Giardia* cysts for specific percent removal of total coliform bacteria. Data from Table A-1 and Table A-2 plotted in Figure H-13.

previous section, in Figure 38 and 39, and the associated statistical analysis, showed that it could be used as a surrogate for Giardia cyst removal.

Figure 42 is a histogram showing percent removal of total coliform bacteria and corresponding values of percent removal of turbidity. The historgram shows a strong association between the two variables. When percent removals of turbidity exceed 80 then percent removals of total coliform bacteria exceed 80 also. Figure G-16 shows all data plotted, along with the results of the student t-distribution. The analysis shows that a positive association exists, with 99.5 percent confidence level. Figure G-17 shows that "probability of occurrence" plot corresponding to the data shown in Figure G-16. It shows for example that if percent removal of turbidity exceeds 80, then there is 0.95 probability that percent removal of total coliform will exceed 80.

Figures G-18 and G-19 in Appendix G show similar data and results between percent removal of turbidity and percent removal of standard plate count bacteria. The student t-distribution test of data in Figure G-16 shows again the 99.5 percent confidence that a positive functional relationship exists. Figure G-19, for the probability of occurrence plot of data in Figure G-18, shows a generally lower family of curves than seen for total coliform bacteria.

Figure G-20 and G-21 in Appendix G show similar data and results between percent removal of turbidity and percent removal of particles. The student t-distribution test of data in Figure G-20 shows again the 99.5 percent confidence that a positive functional relationship exists. But examination of the family of curves in Figure G-21 for the probability of occurrence plot shows that the curves are still lower than seen for the standard plate count. For example, if turbidity removal is 80 percent the probability that particle removal is 80 percent is 0.86, whereas the probability was 0.95 for the turbidity-coliform data.

FIELD-SCALE PILOT PLANT TESTING

The objective of the field-scale testing was to confirm findings from the laboratory-scale experiments concerning the role of chemicals and the dosages of chemicals in determining removal efficiencies of Giardia cysts, turbidity, and total coliform bacteria, with particular reference to low turbidity waters. To conduct this testing the pilot plant was set up to obtain water from the Cache La Poudre in its mountain canyon, at the site of Fort Collins Water Treatment Plant No. 1. The work was conducted during the period October 1983 to January 1984, when raw water turbidities are usually less than 1 NTU. The results are reported in this section. It should be noted that testing using the field-scale pilot plant was more limited than when using the laboratory-scale pilot plant. This was due first to the logistic problems of conducting field-scale testing. But also to conduct tests using low turbidity water, it was necessary to find "windows of opportunity", with respect to weather, and sometimes other factors.

Test Conditions

Run number(s)	: 135 test run
Raw water turbidity	: 0.2-1.4 NTU
Temperature	: 2-18C
Coagulant	: All pretreatment condition

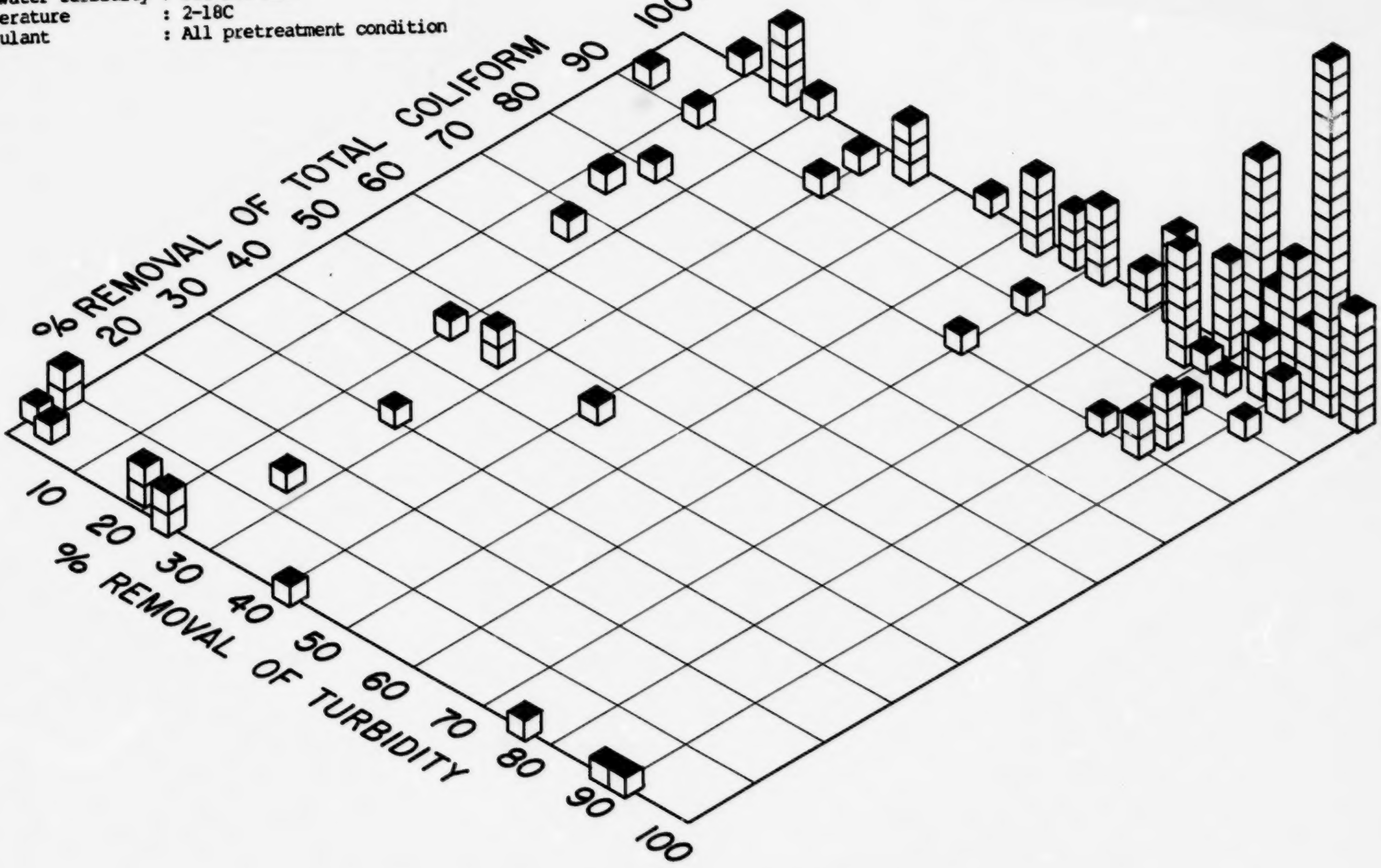


Figure 42. Histogram showing percent removal of total coliform removal with corresponding percent removal of turbidity. Each block represents one measurement set. Data points are for all water tested.

Testing was done also using other waters when low turbidity Cache La Poudre River was was not available and included water from the Cache La Poudre River during spring runoff and water from Horsetooth Reservoir. These results are given in Appendix H.

The low-turbidity testing phase using raw water from the Cache La Poudre River was comprised of 32 test runs. Effluent turbidity vs coagulant dose curves were generated for five combinations of coagulant chemicals, with selction based on results obtained from the laboratory-scale pilot plant work. From these curves, "optimum" and "nonoptimum" coagulant dosages were defined as the dosage range causing minimum effluent turbidities with respect to the turbidity-dose curve, and dosages which given significantly higher effluent turbidities. Evaluations of Giardia cyst and coliform bacteria removals were done in nine tests for coagulant dosages of "none", "optimum", and "nonoptimum". The "none" test category means that coagulant chemicals were not used.

Coagulant Dosage Determination - Field Scale Pilot Plant

Table 18 shows the results of the 23 effluent turbidity vs coagulant dose tests which used low-turbidity water from the Cache La Poudre River. Five coagulants and coagulant combinations were used in this testing, with selection based upon the lab-scale experiments. From the data in Table 18 effluent turbidity vs coagulant dose plots were generated, shown as Figures 43 through Figure 47, for Nalco 8102, Nalco 8102 and alum, alum, Magnifloc 572-C, and Magnifloc 572-C and alum, respectively.

Of these five figures, Figures 43, 46, and 47 are typical U-shaped curves; Figures 44 and 45 are not. The finished water turbidities in Figures 3-10 to 3-13 show only 0 to 25 percent reductions compared to raw water turbidities which ranged from 0.45 to 0.8 NTU. Determination of "optimum" dosages are not well defined for these curves, except in Figures 46 and 47. Figure 47 shows the typical U-shaped curve, using alum at different dosages and a fixed dosage of 2.0 mg/L of Magnifloc 572-C, where an "optimum" dosage is well defined. The finished water turbidity was reduced to 0.35 NTU compared to 0.7 NTU for the raw water. Later, in Run 138, during a Giardia test run at "optimum" dosage of alum and Magnifloc 572-C, the turbidity was reduced to 0.20 NTU after two-hours of operation. For the similar water and using the same coagulants, the turbidity was reduced to 0.05 to 0.10 NTU for the lab-scale work.

Effect of Coagulant Dose on Filtration - Field Scale Pilot Plant

Evaluations of removals of Giardia cysts, coliform bacteria, and turbidity were performed using coagulant dosages categorized as "none", "optimum", and "nonoptimum". Nine such evaluations were performed, and are described in Table 19, for low-turbidity water.

Table 19. Results of twenty three effluent turbidity vs chemical dose tests using low-turbidity raw water and field-scale rapid rate filtration pilot plant.1/2/ Data points for chemical dose and corresponding effluent turbidity were used to construct Figures 43 through 47.

Run #	Chemical Species3/	Coagulants Chemical Dose4/ mg/L	 Water Temperature (°)	Turbidity (NTU) Influent	 Effluent5/
107	None	0	7	0.55	0.45
108	8102	0.2	7	0.55	0.40
109	8102	0.5	7	0.45	0.50
110	8102	1.0	7	0.50	0.45
111	8102	2.0	7	0.45	0.65
112	8102	0.2	7	0.45	0.35
113	Alum/8102	3.0/0.6	7	0.60	0.75
114	Alum/8102	3.0/0.6	7	0.60	0.75
115	Alum/8102	3.0/0.6	7	0.70	0.70
116	Alum/8102	3.0/0.7	7	0.60	0.60
118	Alum	3.0	2	0.65	0.60
119	Alum	0.5	2	0.65	0.55
120	Alum	1.5	2	0.65	0.55
121	Alum	5.5	2	0.65	0.69
122	Alum	1.0	3	0.65	0.60
130	572-C	0.4	1	0.80	0.65
131	572-C	0.8	1	0.80	0.60
132	572-C	2.0	1	0.80	1.60
133	Alum/572-C	1.5/0.7	1	0.80	0.50
134	Alum/572-C	15/2.0/1/0.70/1.00			
135	Alum/572-C	4.5/2.0	1	0.70	0.35
136:Alum/572-C	9/2.0	1	0.70	0.35	
137	Alum/572-C	30/2.0	1	0.70	3.00

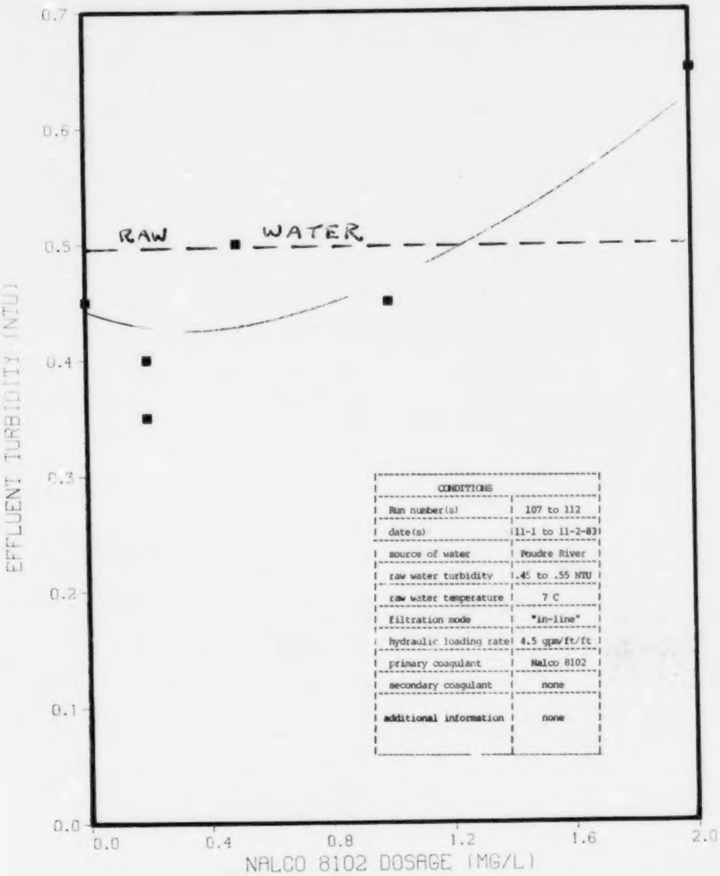
1/Abstracted from Table B-1.

2/Cache La Poudre River water with less than 1 NTU.

3/Nalco 8102, Magnifloc 572-C.

4/Alum doses are mg/L as $Al_2(SO_4)_3$ 14 H_2O.

5/Effluent turbidity after one hour of operation.



CONDITIONS	
Run number(s)	107 to 112
date(s)	11-1 to 11-2-83
source of water	Poudre River
raw water turbidity	.45 to .55 NTU
raw water temperature	7 C
filtration mode	"in-line"
hydraulic loading rate	4.5 gpm/ft/ft
primary coagulant	Nalco 8102
secondary coagulant	none
additional information	none

Figure 43. Effluent turbidity vs Nalco 8102 dose using low-turbidity water, and field-scale rapid rate filtration pilot plant.

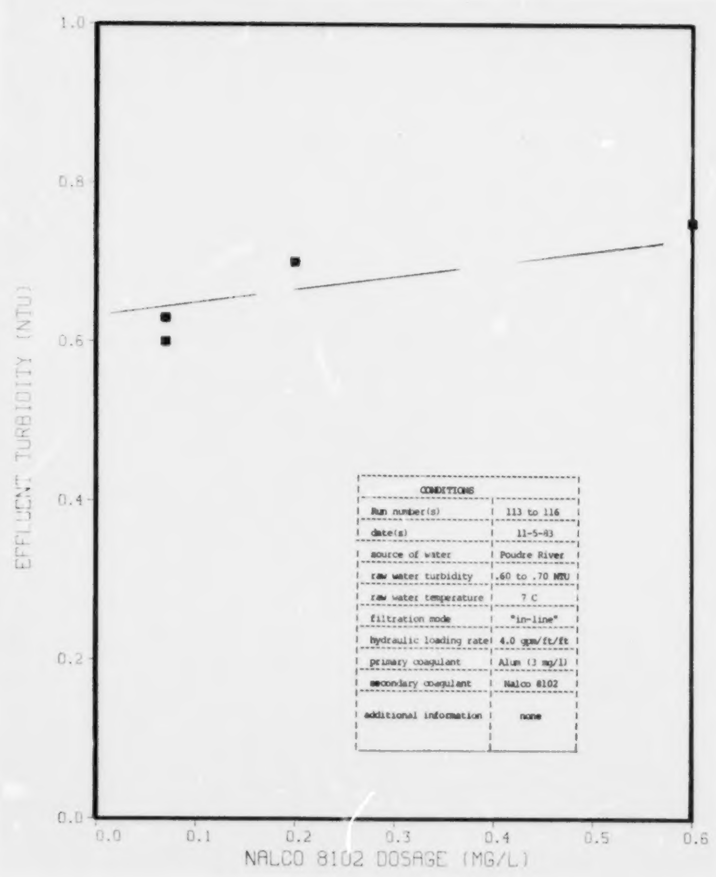


Figure 44. Effluent turbidity vs Nalco 8102 dose using 3 mg/l of alum, $Al_2(SO_4)_3$ 14 H_2O, for low-turbidity water and field scale plant.

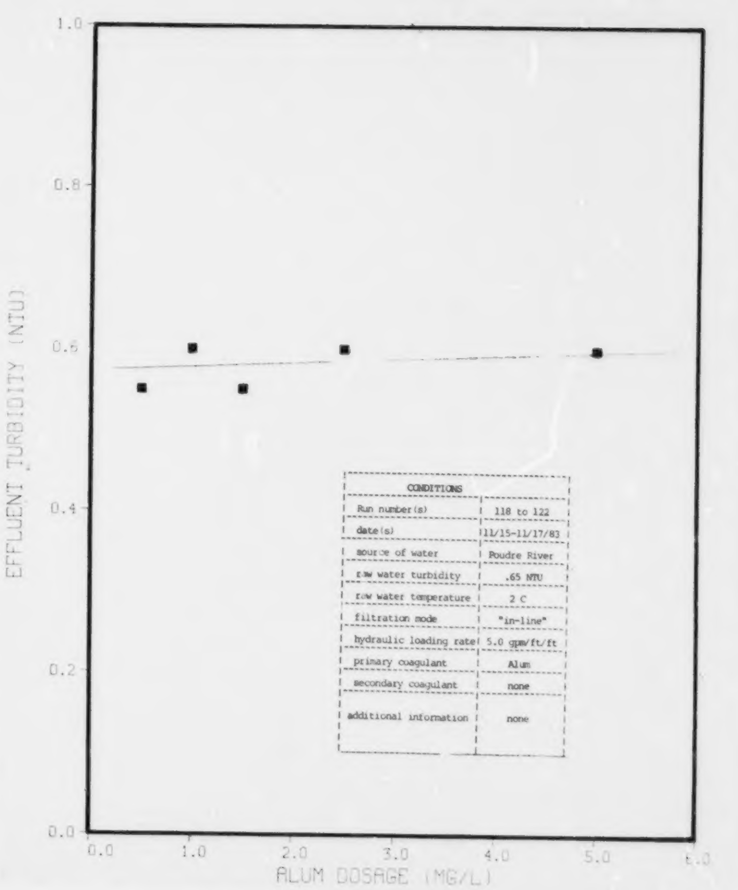
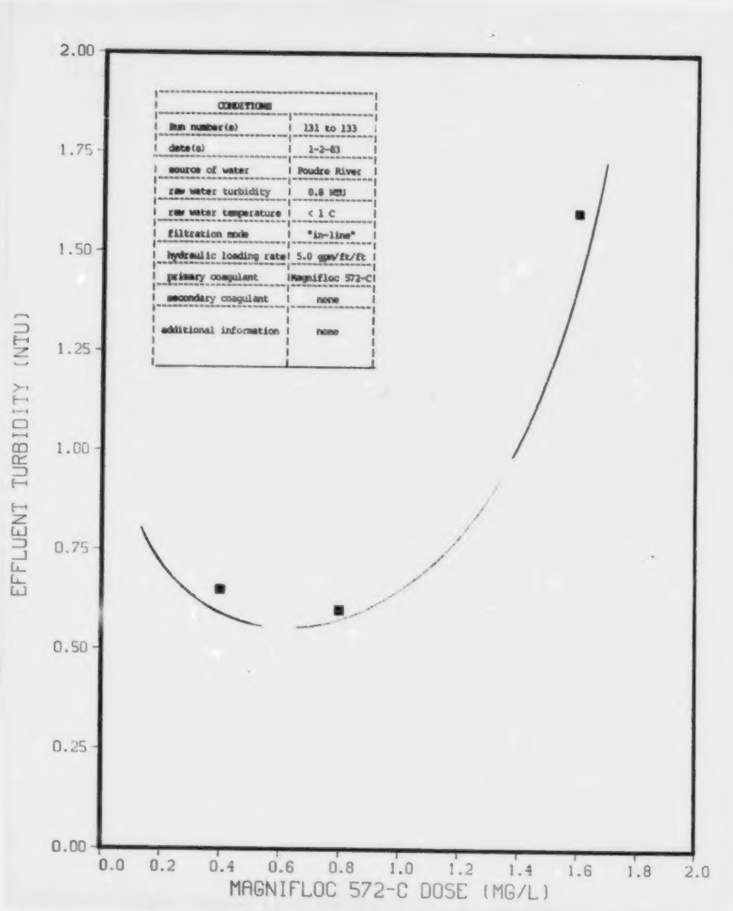
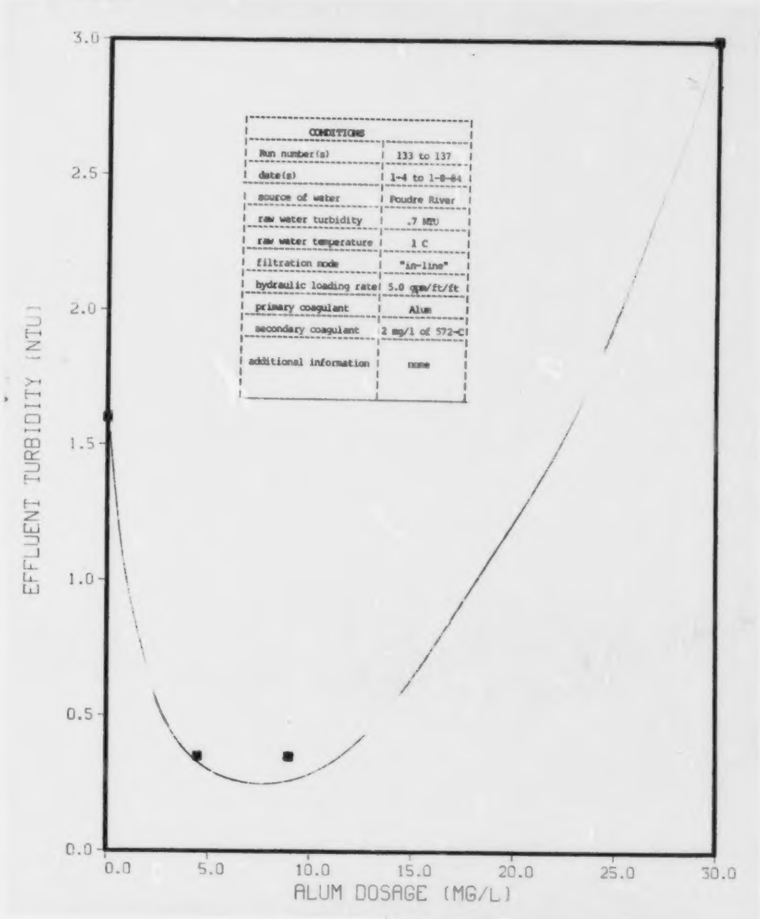


Figure 45. Effluent turbidity vs alum dose, $Al_2(SO_4)_3$ $14H_2O$, for low-turbidity water with field scale pilot plant.



CONDITIONS	
Run number(s)	131 to 133
date(s)	1-2-83
source of water	Poudre River
raw water turbidity	0.8 NTU
raw water temperature	< 1 C
filtration mode	"in-line"
hydraulic loading rate	5.0 gpm/ft/ft
primary coagulant	Magnifloc 572-C
secondary coagulant	none
additional information	none

Figure 46. Effluent turbidity vs dose of Magnifloc 572-C. Low-turbidity water. Field scale pilot plant.



CONDITIONS	
Run number(s)	133 to 137
date(s)	1-4 to 1-8-84
source of water	Poudre River
raw water turbidity	.7 NTU
raw water temperature	1 C
filtration mode	"in-line"
hydraulic loading rate	5.0 gpm/ft/ft
primary coagulant	Alum
secondary coagulant	2 mg/l of 572-C
additional information	none

Figure 47. Effluent turbidity vs alum dose, $Al_2(SO_4)_3 \cdot 14H_2O$, using 2 mg/l of Magnifloc 572-C for low-turbidity water. Field scale.

Table 19. *Giardia* and coliform results from testing using low-turbidity raw water.1/2/ Field scale rapid rate filtration pilot plant.

Run No.	Coagulant Dosage Category11/	Coagulants Used		Water Temperature (NTU)	Turbidity			Giardia Cyst 5/7/			Coliforms8/		
		Chemical3/ (mg/L)	Chemical Dose4/ (°C)		Influent10/ (NTU)	Effluent9/ Removal	Percent cysts/liter	Influent5/ cysts/liter	Effluent6/ Removal	Percent No./100 mL	Influent5/ No./100 mL	Effluent6/	Percent Removal
117	None	None	0	2	0.4	0.6	<1	260	180	30	15000	12000	20
129	None	None	0	1	0.6	0.7	<1	**	**	**	3500	3000	15
123	Optimum	8102	0.1	1	0.6	1.1	<1	325	180	45	6900	5700	20
124	Optimum	8102	0.4	1	0.6	0.85	<1	325	100	40	6900	3500	50
138	Optimum	Alum/572-C	7.0/2.0	<1	0.7	0.4	42	1300	70	95	10000	150	>98
125	Nonoptimum	Alum	0.4	1	0.55	1.0	<1	1300	850	35	9000	8500	10
126	Nonoptimum	Alum	5.0	1	0.55	1.0	<1	1300	950	30	9000	6500	30
127	Nonoptimum	Alum/8102	3.0/0.2	1	0.9	1.1	<1	175	100	45	*	*	*
128	Nonoptimum	Alum/8102	3.0/0.4	1	0.9	0.9	<1	175	125	30	*	*	*

1/ Abstracted from Table B-1
2/ Cache La Poudre River water having raw water turbidities less than 1 NTU
3/ Nalco 8102, Magnifloc 572-C
4/ Alum doses are mg/L as $Al_2(SO_4)_3$ $14H_2O$
5/Detected cyst concentrations, sampling influent stream after mixing by four elbows and before injection of coagulants. Membrane filters used were Nucleopore polycarbonate 5 micrometer pore size, 293 mm diameter. Samples were analyzed by micropipette technique.
6/ Procedures were the same as used for influent sampling and analysis.
7/ Double asterisk indicates cysts were of questionable viability
8/ Single asterisk indicates no data; missed dilution range
9/ Effluent turbidity after one hour of filtration
10/Influent turbidity prior to contaminant injection
11/Reference should be made to Figures 3-10 to 3-14 to judge coagulant dosage with respect to turbidity reductions.

Tests With No Coagulation

Runs 117 and 129, in Table 19 show results obtained for coagulant dosage tests in which Giardia cysts and coliform bacteria were injected into low-turbidity, low-temperature raw waters which were filtered without chemical pretreatment. For the "none" coagulant condition, coliform bacteria removals were 20 and 15 percent, respectively. The Giardia cyst removal of Run 117 was only 30 percent. No Giardia removal data is reported for Run 129 because the cysts were questionable with respect to maintaining identity for analysis. The effluent turbidity was greater than the influent turbidity for each of these "no chemical" runs.

Optimum Coagulant Dose Tests--

Chemical dosages for Runs 123, 124 and 138 were classified as "optimum". For Runs 123 and 124 removals of Giardia cysts were 45 and 40 percent, respectively, coliform removals were 20 and 50 percent, while turbidity removal were less than one percent. The chemicals used in these runs were found to be not effective in the laboratory-scale work and so the field-scale testing corroborates this.

For Run 138, however, removals in all three categories were high, i.e 95 percent for Giardia cysts, 98 percent for coliform bacteria, and 42 percent for turbidity. Coagulant chemicals used for Run 138 were 7.0 mg/L of alum, as $Al_2(SO_4)_3$ 14 H_2O, and 2 mg/L of Magnifloc 572-C. These coagulant dosages were found to be effective in previous bench scale and lab-scale testing. For this test the raw water turbidity was 0.7 NTU, and the effluent turbidity was 0.4 NTU, while the water temperature was $<1^oC$. Higher percent removals of turbidity, e.g. 70 to 80 percent, were found in the laboratory-scale pilot plant results. It should be noted, however, that the water temperature was less than 1^oC (the thermometer measured 0^oC), during Run 138 and so while temperature did not seem to influence filtration down to 3^oC during laboratory-scale work, the 0^oC condition could have an effect.

Nonoptimum Coagulant Dose Tests--

Runs 125 to 128 were classified as "nonoptimum", even though some of the turbidity-dose curves did not show well defined U-shapes. Results for removals of turbidity, coliform bacteria, and Giardia cysts were not significantly different than for the "zero" coagulant dosage tests. It should be noted that chemicals used were those found to be not effective during laboratory-scale pilot plant work.

Associations Between Dependent Variables

Figure 48 is a plot of data taken from Table 19 showing percent removal of Giardia cysts plotted against percent removal of coliform bacteria. Figure 48 indicates that high removals of Giardia cysts can be expected when high removals of coliform bacteria occur. Again, this is consistent with findings in lab-scale experiments with low-turbidity water. It is consistent also with results for Horsetooth water. Other associations were not made because of limited data for the low-turbidity testing phase.

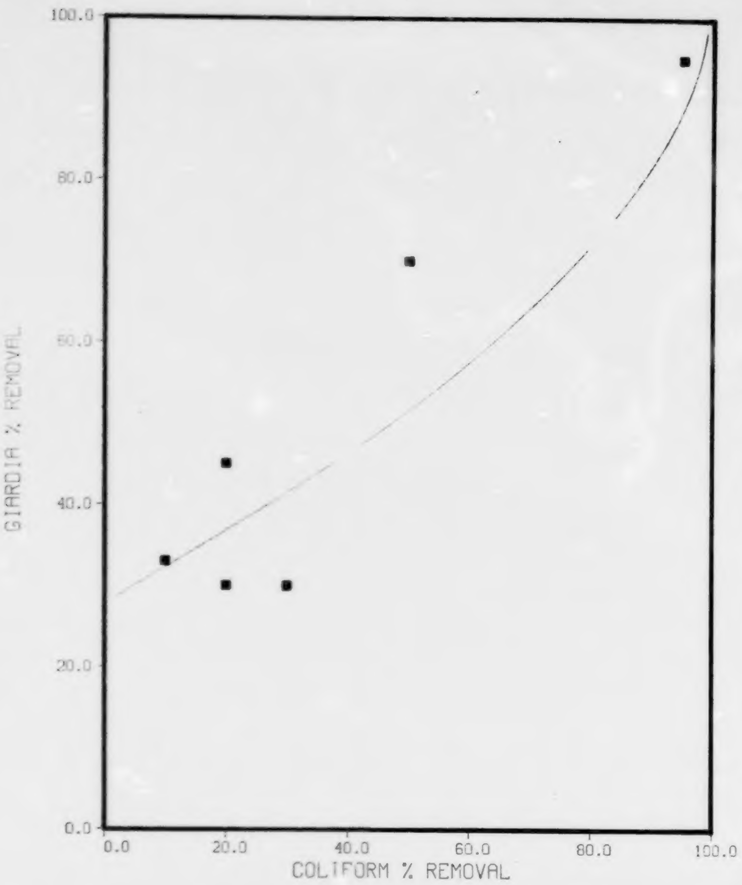


Figure 48. Percent removal of Giardia cysts vs percent removal of coliform bacteria for low-turbidity water. Raw water characteristics were: <1°C and <1 NTU. Field scale pilot plant was used.

Horsetooth Water

Results of field-scale pilot plant testing using raw water from Horsetooth water are given in Appendix H. The turbidity of Horsetooth Reservoir water is about 4 to 10 NTU, and it is more easily treatable by a wider range of chemical coagulants. Some polymers not effective for the low turbidity waters were effective when using Horsetooth water. Percent removals of turbidity, Giardia cysts, and total coliform bacteria were generally 90-97, 95-99, and 97-99, respectively when chemical pretreatment was used. When no chemical pretreatment was used, percent removals were generally 3-14, 27-33, and 0-41, respectively for the turbidity, cysts, and bacteria.

Summary of Results for Field-Scale Pilot Plant Testing

The field-scale pilot plant testing underlines the importance of using chemical coagulants in the rapid rate filtration process. Further, not all coagulants are effective, and so selection of coagulant chemicals is important. Chemicals can be selected and dosages can be determined by generating the classical turbidity-dose curves using a pilot plant. If percent removal of turbidity is high, the percent removal of *Giardia* cysts and total coliform bacteria should be high also.

REFERENCES

Al-Ani, M., and D. W. Hendricks, "Rapid Sand Filtration of Giardia Cysts," Proceedings of ASCE Environmental Engineering Division National Conference, Boulder, Colorado, 1983.

Al-Ani, M., Brink, D., Silverman, G., Lange, K., Bellamy, W. D., McElroy, J., Hendricks, D. W., "Removal of Giardia lamblia from water supplies appropriate treatment technologies for small systems," Quarterly Report, March 1, 1983 to May 31, 1983, Environmental Engineering Report 5847-83-2, Colorado State University, Fort Collins, Colorado, June 1983.

Amirtharajah, A., and K. A. Mills, "Rapid-Mix Design for Mechanisms of Alum Coagulation," J. AWWA, Vol. 74, pp. 210-216, April 1982.

Baker, M. N., "The quest for pure water," prepared by AWWA, printed by Lancaster Press, Inc., Lancaster, Pennsylvania, 1949.

Baylis, J. R., "The efficiency of rapid sand filters in removing the cysts of the amoebic dysentery organisms from water," Public Health Reports, Vol. 51, No. 46, November 13, 1936.

Baylis, J. R., Gullans, O., and Hudson, E. J., Jr., Chapter 7a, Filtration, in "Water quality and treatment," prepared by American Water Works Association, 3rd edition, McGraw-Hill, New York, pp. 245-281, 1971.

Bellamy, W. D., Silverman, G. S., and D. W. Hendricks, "Filtration of Giardia cysts and other substances, Volume II: Slow sand filtration," Report EPA- , U.S. Environmental Protection Agency, Cincinnati, Ohio, April 1985.

Bellamy, W. D., Lange, K. P., and Hendricks, D. W., "Filtration of Giardia cysts and other substances, Volume I: Diatomaceous earth filtration," Report EPA-600/2-84-111, U.S. Environmental Protection Agency, Cincinnati, Ohio, June 1984.

Bellamy, W. D., M. Al-Ani, G. P. Silverman, K. P. Lange, S. I. Choi, D. G. Howell, C. P. Hibler, and D. W. Hendricks, "Removal of Giardia Lamblia from Water Supplies," Environmental Engineering Technical Report No. 5836-82-4, Department of Civil Engineering, Colorado State University, November 1982.

Benedek, A. and Banesi, J., "Laboratory evaluation of polymeric flocculations," ASCE, Vol. 102, No. EE1, pp. 17-28, February 1976.

Black, A. P., "Chemistry of water treatment, Part I: Coagulation," Water and Sewage Works, April, 1948.

Black, A. P., "Basic mechanisms of coagulation," J. AWWA, Vol. 52, pp. 492-561, April 1960.

Black, A. P. and Hannah, S. A., "Electrophoretic studies of turbidity removal by coagulation with aluminum sulfate," J. AWWA, Vol. 53, pp. 430-452, April 1961.

Black, A. P. and Willems, D. G., "Electrophoretic studies of coagulation for removal of organic color," J. AWWA, Vol. 53, pp. 589-604, May 1961.

Black, A. P. and Smith, A. L., "Determination of the mobility of colloidal particles by microelectrophoresis," J. AWWA, Vol. 54, pp. 926-934, August 1962.

Black and Veatch Consulting Engineers, "Direct Filtration of Lake Superior Water for Asbestiform Fiber Removal," Report EPA-670/2-75-050, U.S. Environmental Protection Agency, June 1975.

Blair, J. R., "Giardia lamblia contamination at Estes Park, Colorado," Unpublished Report, Colorado Department of Health - Water Quality Control Division, December 1979.

Blair, J. R., "Report on Giardia lamblia sampling in the resort areas of Vail and Aspen - winter 1980," Unpublished Report, Colorado Department of Health, Denver, Colorado, December 1980.

Blair, J. R., Division of Drinking Water Quality, Colorado Health Dept., Denver, Colorado, personal communication, 1984.

Brink, D. R., "Bench Evaluation of Coagulants for Low-Turbidity Waters," Master's Thesis, Department of Civil Engineering, Colorado State University, September 1984.

Brink, D. R., et al., "Removal of Giardia lamblia from water supplies--appropriate treatment technology for small systems," Quarterly Report, June 1, 1983 to August 31, 1983, No. 5847-83-3, September 1983.

British Columbia Water and Waste Association, Seminar 1983, "Giardiasis and public water supplies," Richmond, British Columbia, November 1983.

Brodsky, R. E., H. C. Spencer, Jr., and M. G. Schultz, "Giardiasis in American travelers to the Soviet Union," Jour. Infect. Dis., Vol. 130, pp. 319-323.

Busch, P. L. and Stumm, W., "Chemical interactions in the aggregation of bacteria," Environmental Science and Technology, Vol. 2, No. 1, January 1968.

Camp, T. R., "Theory of Water Filtration," Journal Sanitary Engineering Division, ASCE, Vol. 90, No. SA4, pp. 139-168, 1964.

Camp, T. R., Root, D. A., and Bhoota, B. V., "Effect of temperature on rate of floc formation," J. AWWA, Vol. 32, pp. 1913-1927, November 1940.

Choi, S. I., "Coagulation in low turbidity water," Master of Science Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, Spring 1983.

Cleasby, J. L., "Slow sand filtration and direct in-line filtration of a surface water," Water Quality Division, Proceedings of the AWWA Sunday Seminar on Innovative Filtration Techniques, Las Vegas, June 5, 1983.

Cleasby, J. L., "Filtration - back to the basics," AWWA Seminar Proceedings, Coagulation and Filtration, Back to the Basics, June 7, 1971.

Cleasby, J. L. and Baumann, R., "Selection of sand filtration rates," J. AWWA, Vol. 55, pp. 599-603, May 1962.

Clifford, J. L., "The role of limestone in the environmental field," Colorado Mining Association Mining Yearbook, 1974.

Colorado Disease Bulletin, Vol. XII, No. 7, Colorado Dept. of Health, Denver, Colorado, March 31, 1984.

Committee Report, "Survey of polyelectrolyte coagulant use in the United States," J. AWWA, Vol. 74, pp. 600-608, 1982.

Conley, W. R., "Experience with anthracite sand filters," J. AWWA, Vol. 53, pp. 1473-1483, December 1961.

Craun, G. F., "Waterborne outbreaks of giardiasis," in Waterborne Transmission of Giardiasis, United States Environmental Protection Agency, EPA-600/9-79-001, p. 137, June 1979.

Davies, R. B. and Hibler, C. P., "Animal reservoirs and cross-species transmission," Waterborne Transmission of Giardiasis, Environmental Protection Agency, Proceedings of Symposium, September 18-20, 1978.

Davies, R. B., Fukutaki, K., and Hibler, C. P., "Cross transmission of Giardia," NTIS Report No. PB83-117-747, Cincinnati, Ohio, January 1983.

DeWalle, F. B. and Erland Jansson, C. R., "Chlorine and ultraviolet water treatment to ensure inactivation of Giardia," Seminar, Richmond, British Columbia, November 1983.

DeWalle, F. B., J. Engeset, W. Lawrence, "Removal of Giardia Lamblia Cysts in Drinking Water Treatment Plants," EPA-600/2-84-069, U.S. Environmental Protection Agency, Cincinnati, Ohio, March 1984.

Edzwald, J. K., "Coagulation," AWWA Sunday Seminar, Coagulation and Filtration, Back to the Basics, AWWA Annual Conference, St. Louis, Missouri, June 1981.

Edzwald, J. K. and Lawler, D. F., "Mechanisms of particle destabilization for polymers in water treatment," AWWA Sunday Seminar "Use of Organic Polyelectrolytes in Water Treatment," AWWA Annual Conference, Las Vegas, Nevada, June 1983.

Garnell, M. A., "Effect of a polyelectrolyte as filter aid," J. AWWA, Vol. 55, pp. 597-601, May 1963.

Hendricks, D. W., "Unit operations," Class Notes for CE540,541, Dept. of Civil Engineering, Colorado State University, Fort Collins, Colorado, 1976.

Hewlett, E. L., Andrews, J. S., Ruffier, J., and Schaefer, F. W. III, "Experimental infection of mongrel dogs with Giardia lamblia cysts and cultured trophozoites," Journal of Infectious Diseases, Vol. 145, No. 1, pp. 89-93, 1982.

Hibler, C. P., Pathology Department, Colorado State University, Fort Collins, Colorado, personal communication, May 4, 1984.

Hudson, H. E., Jr., "Water clarification processes: practical design and evaluation," Van Nostrand Reinhold Company, 1981.

Hudson, H. E., Jr. and Wolfner, J. P., "Design of mixing and flocculating basins," J. AWWA, Vol. 59, pp. 257-1267, Oct. 1967.

Ives, J., "New concepts in filtration. Part 3: Surface force concepts, and conclusions," Water and Water Engineering, pp. 385-388, September 1961.

Ives, K., "The scientific basis of flocculation," NATO Advanced Study Institutes Series, Series E: Applied Science, No. 27, 1977.

Ives, K. J., "The scientific basis of filtration," Proceedings of the NATO, Cambridge, United Kingdom, July 2-20, 1975.

Jakubowski, W. and Hoff, J. C., Waterborne Transmission of Giardia, USEPA, Cincinnati, Ohio, Report No. EPA-600/9-79-001, 1979.

Johnson, P. N. and Amirtharajah, A., "Ferric Chloride and Alum as Single and Dual Coagulants," Journal AWWA, Vol. 109, pp. 232-239, May 1983.

Karlin, R. and Hopkins, R., "Engineering defects associated with Colorado giardiasis outbreaks," AWWA Annual Conference, Las Vegas, June 5-9, 1983.

Kirmeyer, G. J., "Seattle Tolt Water Supply Mixed Asbestiform Removal Study," Report EPA-600/2-79-125, U.S. Environmental Protection Agency, August 1979.

Lange, K. P., "Removal of Giardia lamblia cysts and other substances by diatomaceous earth filtration," M.S. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, Spring 1983.

Langelier, W. F., Ludwig, H. F., "Mechanism of flocculation in the classification of turbid waters," J. AWWA, Vol. 41, February 1949.

Langelier, W. F., "Coagulation of water with alum by prolonged agitation," Engineering News Record, Vol. 86, No. 22, June 2, 1921.

Leipoid, C., "Mechanical agitation on alum floc formation," J. AWWA, Vol. 26, p. 1070, 1934.

Levine, N. D., "Giardia lamblia classification, structure, identification," Waterborne Transmission of Giardia, EPA-600/9-79-001, pp. 2-8, June 1979.

Logsdon, G. S., "Water Filtration for Asbestos Fiber Removal," Report EPA/2-79/206, U.S. Environmental Protection Agency, December, 1979.

Logsdon, G. S., Symons, J. M., Hoye, R. L., Jr., and M. M. Arozarena, "Alternative filtration methods for removal of Giardia cysts and cyst models," J. AWWA, Vol. 73, No. 2, pp. 111-118, 1981.

Logsdon, G. S., and Kim, R., "Getting your money's worth from filtration," JAWWA, pp. 249-256, May 1982.

Logsdon, G. S., Evavold, G. L., Patton, J. L., and Watkins, J. Jr., "Filter plant design for asbestos fiber removal," Journal of Environmental Engineering, American Society of Civil Engineers, Vol. 109, No. 4, pp. 900-914, August 1983.

Logsdon, G., EPA, Drinking Water Division, Cincinnati, Ohio, personal communication, May 3, 1984.

Logsdon, G. S., "Direct filtration - past, present, future," Civil Engineering ASCE, Series on Water Resource, No. 7, July 1978.

Luchtel, D. L., Lawrence, W. P. and DeWalle, F. B., "Electron microscopy of Giardia lamblia cysts," Appl. and Envir. Micro., 4084, pp. 821-832, 1980.

McElroy, J. M. and D. W. Hendricks, "Field-Scale Evaluation of Coagulants for Filtration of *Giardia* Cysts and Other Substances," Environmental Engineering Technical Report No. 5847-84-2, Department of Civil Engineering, Colorado State University, April 1984.

Microbiological Methods for Monitoring the Environment, Water and Wastes, Edited by R. Bordner and J. Winder, EPA Publication 600/8-78-017, U.S. Environmental Protection Agency, Cincinnati, 1978.

Mohtadi, M. F., and Rao, P. N., "Effect of temperature on flocculation of aqueous dispersions," *Water Research*, Vol. 7, No. 5, pp. 747-767, 1973.

O'Melia, C. R. and Crapps, D. K., "Some chemical aspects of rapid sand filtration," *J. AWWA*, Vol. 56, pp. 1326-1344, October 1964.

O'Melia, R. C. and Stumm, W., "Theory of water filtration," *J. AWWA*, Vol. 59, pp. 1393-1412, November 1967.

O'Melia, C. R., "Review of the coagulation process," Public Works, pp. 87-98, May 1969.

O'Melia, C. R., "The role of polyelectrolytes in filtration processes," EPA Technology Series, University of North Carolina, Chapel Hill, North Carolina, April 1974.

Parker, D. S., et al., "Floc break-up in turbulent floccuation processes," *ASCE*, Vol. 98, No. SA1, February 1972.

Pasaris, P. J. and Hendricks, D. W., "Fecal coliform densities in a western watershed," *Water, Air, and Soil Pollution*, Vol. 17, pp. 253-262, 1982.

Pilipavich, J. B., Black, A. P., Eidsness, F. A., and Stearnes, T. W., "Electrophoretic studies of water coagulation," *J. AWWA*, Vol. 50, pp. 1467-1482, November 1958.

Pluntze, J. C., "The significance of giardiasis on water quality standards and water utility practice in Washington state," a paper presented at the Workshop on Giardiasis, British Columbia Water and Waste Association; Vancouver, British Columbia, November 22, 1983.

Pugh, T. L., Heller, W., "Coagulation and stabilization of colloidal solution with polyelectrolytes," *Journal of Polymer Science*, Vol. XLVII, pp. 219-227, 1966.

Rendtorff, R. C., "The experimental transmission of human intestinal protozoan parasites: *Giardia lamblia* cysts given in capsules," *Am. J. Hyg.*, 59:209-220, 1954.

Riddick, T. M., "Zeta potential and its application to difficult water," *J. AWWA*, Vol. 53, pp. 1007-1038, August 1961.

Rouse, H., *Elementary Mechanics of Fluids*, Dover Publication, Inc., New York, July 1945.

Robeck, G. G., Dostal, K. A., and Woodward, R. L., "Studies of modification in water filtration," *J. AWWA*, Vol. 56, pp. 198-213, February 1964.

Rubin, A. J. and Hanna, G. P., "Coagulation of bacterium *Escherchia Coli* by aluminum nitrate," *Environmental Science and Technology*, pp. 358-362, Vol. 2, No. 5, May 1968.

Sanks, L., *Water Treatment Plant Design*, Ann Arbor Science, Ann Arbor, Michigan, 1978.

Sato, A., Konno, H., "Basic consideration on factors affecting rapid sand filtration," *Tech. Report*, Tohohu University, Vol. 44, No. 2, 1979.

Schleppenbach, Frank X., *Water Filtration at Duluth*, EPA-600/2-84-083, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, Ohio, April 1984.

Shaw, P. K., Brodsky, R. E., Lyman, D. O., Wood, B. T., Hibler, C. P., Healy, G. R., Macleod, K. I. E., Stahl, W., and Schultz, M. G., "A community-wide outbreak of giardiasis with evidence of transmission by a municipal water supply," *Annals Intr. Med.*, Vol. 87, No. 4, pp. 426-432.

Silverman, G. P., "Behavior of Slow Sand Filters - Emphasis on the Removal of *Giardia Lamblia* Cysts," Master's Thesis, Department of Civil Engineering, Colorado State University, Summer 1983.

Silverman, G. P., W. D. Bellamy, and D. W. Hendricks, "Slow Sand Filtration of *Giardia Lamblia* Cysts and Other Substances" Phase I Report, Environmental Engineering Technical Report No. 5847-83-4, Department of Civil Engineering, Colorado State University, September 1983.

Spink, C. M. and Monscvitz, J. T., "Design and operation of a 200-mgd direct-filtration facility," *J. AWWA*, Vol. 66, pp. 127-132, 1974.

Standard Methods for the Examination of Water and Waste Water, 15th Edition, 1980.

Steel, E. W. and McGhee, T. J., "Water supply and sewerage," Fifth Edition, McGraw-Hill, 1979.

Stumm, W., "Chemical interaction in particle separation," Environmental Science and Technology, Vol. 11, No. 12, 1977.

Stumm, W. and Morgan, J. J., "Chemical aspects of coagulation," *J. AWWA*, Vol. 54, pp. 971-993, August 1962.

Stumm, W. and O'Melia, C. R., "Stochiometry of coagulation," J. AWWA, Vol. 60, pp. 514-539, May 1968.

Tate, C. H., Lang, S. J., and Hutchinson, H. L., "Pilot plant tests of direct filtration," J. AWWA, Vol. 69, No. 7, pp. 379-384, July 1977.

Veh, H. H., and M. M. Ghosh, "Selecting Polymers for Direct Filtration," JAWWA, pp. 211-218, April 1981.

Velz, C. J., "Influence of temperature on coagulation," Civil Eng., Vol. 4 No. 7, pp. 345-349, July 1934.

Visvesvara, G. S. and G. R. Healy, "The possible use of an indirect immunofluorescent test using axenically grown Giardia lamblia antigens in diagnosing giardiasis," Waterborne Transmission of Giardia, EPA, Proceedings of a Symposium, September 18-20, 1978.

Weber, W. J., Jr., Physicochemical Processes for Water Quality Control, Wiley-Interscience, New York, 1972.

APPENDIX A

All reduced data and results from the laboratory-scale testing are included in Tables A-1 and A-2. Table A-1 summarizes all test conditions and results, categorized by test identification, influent water characteristics, chemical basin conditions, filter conditions, and filter effluent data. It contains all data obtained during test runs of the laboratory scale rapid rate filtration pilot plant. Each row in the table constitutes the data obtained during a given test run. The table can be read by each page using Run No. and Col. No. to coordinate between pages. Alternatively a large table can be constructed from the pages of Table A-1 by cutting along the match marks indicated on each sheet and using the Run No. and Col. No. as guides to place the sheets.

Table A-2 contains effluent results of *Giardia* cyst testing corrected for sampling efficiency data and detection limits. The basic data were obtained from Table A-1. It should be noted that *Giardia* cysts were not used in Runs 1-41. The use of cysts to spike the influent water in the milk cooler was deferred until this time in order to become familiar with operation of the pilot plant and to do preliminary testing.

Table A-1. Master data table for laboratory-scale rapid-rate filtration pilot plant (page 1 of 12).

Test IDENTIFICATION		INFLUENT WATER CHARACTERISTIC						
Date (1)	Run No. (2)	Temperature (°C) (3)	Turbidity (NTU) (4)	Particle Count (No./10 ml) 2.52 - 0.8 µm (5)	Standard Plate Count (No./ml) (6)	Total Coliform (No./100 ml) (7)	Giardia Cyst Designed (cysts/l) (8)	Giardia Cyst Detected (cyst/l) (9)
5-13-82	1	6.5	6.00H	-	-	-	0.00	0.000
5-13-82	1	6.5	6.00H	-	-	-	0.00	0.000
5-31-82	2	7.0	3.60H	74,265	59,000	10,500	0.00	0.000
5-31-82	2	7.0	3.60H	74,265	59,000	10,500	0.00	0.000
6- 2-82	3	11.0	3.00H	18,892	7,000	230	0.00	0.000
6- 2-82	3	11.0	3.00H	18,892	7,000	230	0.00	0.000
6- 4-82	4	16.0	3.80H	35,380	97,000	10,000	0.00	0.000
6- 4-82	4	16.0	3.80H	35,380	97,000	10,000	0.00	0.000
6- 8-82	5	11.0	3.70H	36,181	36,000	9,000	0.00	0.000
6- 8-82	5	11.0	3.70H	36,181	36,000	9,000	0.00	0.000
6-10-82	6	13.0	3.50H	38,266	-	-	0.00	0.000
6-10-82	6	13.0	3.50H	38,266	-	-	0.00	0.000
6-14-82	7	14.0	3.20H	45,241	25,300	350,000	0.00	0.000
6-14-82	7	14.0	3.20H	45,241	25,300	350,000	0.00	0.000
6-16-82	8	14.0	3.30H	41,904	27,000	180,000	0.00	0.000
6-16-82	8	14.0	3.30H	41,404	27,000	180,000	0.00	0.000
6-17-82	9	14.0	3.30H	53,498	387,000	54,000	0.00	0.000
6-18-82	10	14.5	3.30H	-	161,300	6,100	0.00	0.000
6-23-82	11	14.5	3.50H	-	127,000	6,400	0.00	0.000
6-23-82	11	14.5	3.30H	-	127,000	6,400	0.00	0.000
6-25-82	12	16.0	3.30H	7032	28,000	1,250	0.00	0.000
6-25-82	12	16.0	3.30H	7032	28,000	1,250	0.00	0.000
7- 6-82	13	16.0	4.20H	228,036	15,000	1,595	0.00	0.000
7- 7-82	14	14.5	4.50H	123,593	11,300	2,000	0.00	0.000
7-13-82	15	13.5	3.40H	73,540	13,600	800	0.00	0.000
7-14-82	16	14.5	3.70H	71,485	20,000	805	0.00	0.000
7-19-82	17	13.0	3.70H	-	-	-	0.00	0.000
7-21-82	18	13.0	0.60H	7860	5,700	4	0.00	0.000
7-22-82	19	20.0	0.58H	-	-	-	0.00	0.000
7-26-82	20	20.5	0.41H	32,048	464,000	50	0.00	0.000
7-27-82	21	21.0	0.42H	58,247	399,000	70	0.00	0.000
7-28-82	22	21.0	0.42H	58,247	399,000	70	0.00	0.000
7-29-82	23	16.0	0.91H	26,856	-	220	0.00	0.000
7-30-82	24	18.5	0.91H	26,856	286,500	110	0.00	0.000
8- 2-82	25	20.0	0.91H	26,856	286,500	110	0.00	0.000
8- 4-82	26	21.0	0.13H	-	-	-	0.00	0.000
8- 6-82	27	20.0	0.22H	-	286,500	110	0.00	0.000
8- 9-82	28	20.0	0.16H	-	4,150	50	0.00	0.000
8-10-82	29	20.0	0.16H	-	4,150	50	0.00	0.000
8-12-82	30	13.5	0.17H	-	210	180	0.00	0.000
8-18-82	31	16.0	0.22H	3840	24,500	95	0.00	0.000
8-19-82	32	18.0	0.22H	5599	32,500	650	0.00	0.000
8-20-82	33	18.5	0.22H	5599	32,500	650	0.00	0.000
8-20-82	34	18.5	0.22H	5599	32,500	650	0.00	0.000
8-25-82	35	18.5	0.31H	14,923	-	-	0.00	0.000
8-30-82	36	2.0	0.27H.DE	8,210	21,400	-	-	-
8-31-82	37	2.0	0.19H.DE	-	-	-	-	-
9- 1-82	38	2.0	0.19H.DE	12,616	19,250	210.0	-	-
9- 2-82	39	2.0	0.19H.DE	12,616	14,300	160.0	-	-
9- 3-82	40	2.0	0.19H.DE	12,616	2,750	65.0	-	-
9- 9-82	41	2.0	0.25H.DE	-	-	-	-	-
9-13-82	42	2.0	0.64H.DE	-	-	-	500.8	76.628
9-13-82	43	2.0	0.64H.DE	-	-	-	50.0	81.632
9-15-82	44	2.0	0.76H.DE	-	-	-	500.0	57.866
9-15-82	45	2.0	0.76H.DE	-	-	-	500.0	23.255
9-29-82	46	3.0	0.22H.DE	5,001	1,950	4,000.0	480.6	260.000
9-29-82	47	3.0	0.22H.DE	5,001	1,950	4,000.0	480.6	260.000
9-30-82	48	3.0	0.22H.DE	5,001	1,825	1,300.0	480.6	458.300
10- 4-82	49	2.0	0.29H.DE	5,001	3,650	1,300.0	480.0	458.330
10- 4-82	50	4.0	0.36H.DE	27,613	12,700	45.0	480.6	112.500
10- 5-82	51	3.0	0.36H.DE	34,216	7,125	70.0	480.6	383.330
10- 6-82	52	4.0	0.36H.DE	30,419	16,750	14.0	480.6	522.220
10- 7-82	53	4.0	0.46H.DE	37,380	-	12.5	480.6	372.400
10-12-82	54	4.0	0.35H.DE	-	18,875	1475.0	500.0	340.000

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 2 of 12).

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
10-13-82	55	4.0	0.40H.DE	45,121	29,900	315.0	500.0	404.540
10-14-82	56	4.0	0.47H.DE	63,388	114,500	195.0	500.0	170.000
10-15-82	57	4.0	0.47H.DE	63,388	29,790	96.0	500.0	170.000
10-19-82	58	4.0	0.50H.DE	102,705	84,250	10.0	500.0	225.000
11-23-82	59							
11-23-82	60	3.0	0.34H.DE	-	-	-	-	-
12- 1-82	61	15.0	4.20H.DE	1,248,438	39,000	330.0	461.5	-
12- 2-82	62	4.0	4.20H.DE	675,325	161,000	38.0	461.5	0.000
12- 3-82	63	4.0	4.20H.DE	-	-	-	461.5	0.000
12- 3-82	64	4.0	4.20H.DE	961,881	196,000	6.0	461.5	0.000
12- 7-82	65	4.0	4.30H.DE	961,881	11,350	-	461.5	0.000
12- 4-82	66	3.0	0.45H.DE	39,649	4,625	3500	500	368.750
12-15-82	67	4.0	0.51H.DE	39,629	1,370	10	500	333.330
12-16-82	68	4.0	0.53H.DE	45,606	1,330	42	500	435.480
12-17-82	69	4.0	0.53H.DE	45,606	6,050	100	500	519.230
12-17-82	70	4.0	0.53H.DE	45,606	6,050	100	500	519.230
1- 6-83	71	3.0	0.96H.DE	150,011	175,500	625	1000	628.200
1- 7-83	72	3.0	0.99H.DE	110,814	151,000	50	1000	700.000
1-11-83	73	3.0	1.10H.DE	-	36,750	-	1000	-
1-12-83	74	3.0	1.33H.DE	142,932	35,800	160	1000	416.000
1-14-83	75	3.0	1.33H.DE	144,924	-	-	1000	324.440
1-27-83	76	3.0	0.47H.DE	10,837	-	-	1000	200.000
1-27-83	77	3.0	0.47H.DE	10,837	-	-	1000	200.000
1-27-83	78	3.0	0.47H.DE	10,837	-	-	1000	200.000
1-27-83	79	3.0	0.47H.DE	10,837	-	-	1000	200.000
1-28-88	80	4.0	0.47H.DE	4,377	12,500	22	1000	-
1-31-83	81	3.0	0.48H.DE	14,864	7,100	9	1000	-
2- 1-83	82	3.0	0.59H.DE	,927	30,000	9	1000	-
2- 2-83	83	3.0	0.59H.DE	25,961	-	-	1000	-
2- 8-83	84	3.0	2.2H.DE	-	-	-	5000	2789.470
2- 9-83	85A	3.0	2.2H.DE	115,643	17,500	200,000	5000	3000.000
2- 9-83	85B	3.0	2.2H.DE	115,643	17,500	200,000	5000	3000.000
2-10-83	86A	3.0	2.5H.DE	211,356	30,000	10,000	5000	843.750
2-10-83	86B	3.0	2.5H.DE	211,356	30,000	10,000	5000	843.730
2-11-83	87A	3.0	2.5H.DE	394,600	192,500	100,000	5000	1783.780
2-11-83	87B	3.0	2.5H.DE	394,600	192,500	100,000	5000	1783.780
2-15-83	88A	3.0	3.8H.DE	482,002	300,000	16,400,000	5000	2368.411
2-15-83	88B	3.0	3.8H.DE	482,002	300,000	16,400,000	5000	2368.411
2-16-83	89A	3.0	3.8H.DE	785,263	665,000	12,600,000	5000	2650.000
2-16-83	89B	3.0	3.8H.DE	785,263	665,000	12,600,000	5000	2650.000
2-17-83	90A	3.0	2.2H.DE	21,570	-	46,000	5000	4040.4001
2-17-83	90B	3.0	2.2H.DE	21,570	-	46,000	5000	4040.4001
2-18-83	91A	3.0	2.4H.DE	90,836	277,500	28,000	5000	3181.8181
2-18-83	91B	3.0	2.4H.DE	90,836	277,500	28,000	5000	3181.8181
2-22-83	92A	3.0	9.6CLP	-	-	-	10,000	-
2-22-83	92B	3.0	9.6CLP	-	-	-	10,000	-
2-23-83	93A	3.0	9.6CLP	-	-	-	10,000	-
2-23-83	93B	3.0	9.6CLP	-	-	-	10,000	-
2-28-83	94	3.0	1.7CLP	75,465	101,500	20,000	787	753.850
2-28-83	95	3.0	1.7CLP	75,465	101,500	20,000	787	753.850
2-28-83	96	3.0	1.7CLP	75,465	101,500	20,000	787	753.850
2-28-83	97	3.0	1.7CLP	75,465	101,500	20,000	787	753.850
3- 2-83	98	3.0	2.4CLP	83,427	175,000	-	500	1025.640
3- 3-83	99	3.0	3.2CLP	49,666		59,000	1500	1012.130
3- 8-83	100	4.0	3.2CLP	61,053	-	-	6000	975.600
3-14-83	101A	4.0	4.8CLP	494,482	277,000	83,000	700	159.760
3-14-83	101B	4.0	4.8CLP	494,482	277,000	83,000	700	159.760
3-15-83	102A	3.0	6.2CLP	63,696	30,000	14,000	700	422.080
3-15-83	102B	3.0	6.2CLP	63,696	30,000	14,000	700	422.080
3-23-83	103	3.5	1.08CLP	-	105,000	5000	602	408.160
3-24-83	104A	3.5	1.08CLP	80,805	60,500	450	602	56.690
3-24-83	104B	3.5	1.08CLP	80,805	60,500	450	602	56.690
3-25-83	105	14.0	1.08CLP	80,759	9,300	1010	602	-
3-28-83	106	3.5	0.51CLP	82,013	15,000	45	440	183.10
3-31-83	107A	3.0	0.68CLP	59,007	30,500	10	594	298.270
3-31-83	107B	3.0	0.68CLP	59,007	30,500	10	594	298.270
4- 1-83	108	7.0	0.60CLP	43,554	21,000	-	0	0.000
4- 7-83	109	9.0	1.04CLP	97,820	16,000	4500	0	0.000
4- 8-83	110	2.0	1.14CLP	80,074	160	150	0	0.000
4-14-83	111	3.5	1.13CLP	71,716	30,000	1500	240	233.160
4-14-83	112	3.5	1.13CLP	71,716	30,000	1500	240	233.160
4-15-83	113	3.5	1.13CLP	60,330	27,500	695	240	115.380

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 3 of 12).

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
4-15-83	114	3.5	1.13CLP	60,330	27,500	695	240	115.380
4-20-83	115	3.0	1.28CLP	45,533	12,500	1400	200	238.940
4-20-83	116	3.0	1.28CLP	45,533	12,500	1400	200	238.940
4-21-83	117	3.0	1.24CLP	34,962	9,000	790		858.180
4-21-83	118	3.0	1.24CLP	34,962	9,000	790		858.180
4-24-83	119	3.0	1.60CLP	72,520	15,500	4650	300	269.000
4-24-83	120	3.0	1.60CLP	72,520	15,500	4650	300	269.000
4-24-83	121	3.0	1.60CLP	72,520	15,500	4650	300	269.000
4-24-83	122	3.0	1.60CLP	72,520	15,500	4650	300	269.000
4-25-83	123	3.0	1.60CLP	72,520	13,000	200	300	245.450
4-25-83	124	3.0	1.60CLP	72,520	13,000	200	300	245.450
5- 3-83	125	3.0	33.00CLP	-	12,500	1900	0	
5- 5-83	126A	3.0	33.00CLP	-	-	35	0	
5- 5-83	126B	3.0	33.00CLP	-	-	35	0	
5-10-83	127A	16.5	14.20CLP	-	5,000	2600	0	-
5-10-83	127B	16.5	14.20CLP	-	5,000	2600	0	-
5-11-83	128A	4.0	14.20CLP	-	12,500	1350	0	-
5-11-83	128B	4.0	14.20CLP	-	12,500	1350	0	-
5-12-83	129	4.0	14.20CLP	-	-	1010	0	-
5-12-83	130	10.0	14.20CLP	-		27	0	
5-16-83	131A	16.0	14.20CLP	-		10	0	-
5-16-83	131B	16.0	14.20CLP	-		10	0	-
5-17-83	132	4.0	14.20CLP	-	36,000	<10	0	-
5-30-83	133	5.0	18CLP	-	18,600	1285	400	450.000
6- 6-83	134	3.0	1.19CDE	-	15,500	12,850	660.7	745.257
6- 6-83	135	3.0	1.19CDE	-	15,500	12,850	660.7	745.257
6- 7-83	136	4.0	1.19CDE	-	15,500	5850	0.0	-
6- 7-83	137	4.0	1.19CDE	-	15,500	5850	0.0	-
6- 8-83	138	3.0	1.19CDE	-	9,450	2350	0.0	-
6- 8-83	139	4.0	1.19CDE	-	9,450	2350	0.0	-
6-13-83	140	12.0	1.19CDE	-	23,700	40	0.0	-
6-13-83	141	13.0	1.19CDE	-	23,700	-	0.0	-
6-14-83	142	14.0	1.19CDE	-	24,800	<1	0.0	-
6-14-83	143	14.0	1.19CDE	-	24,800	<1	0.0	-
6-15-83	144	14.0	1.19CDE	-	900	<1	0.0	-
6-15-83	145	14.0	1.19CDE	-	900	<1	0.0	-
7-19-83	146	3.5	0.89HDE	-	9,420	24,500	605.8	385.700
7-20-83	147	3.5	0.89HDE	-	4,050	7,500	605.8	51.540
7-26-83	148	3.0	1.06HDE	-	51,500	12,500	605.8	75.000
7-27-83	149	3.0	1.06HDE	-	38,000	37,000	-	-
8- 2-83	150	18.0	0.45HDE	-	16,950	7,500	0.0	-
8- 2-83	151	18.0	0.45HDE	-	16,950	7,500	0.0	-
8- 3-83	152	17.0	0.45HDE	-	17,000	1,000	0.0	-
8- 3-83	153	17.0	0.45HDE	-	17,000	1,000	0.0	-
8- 5-83	154	18.0	0.45HDE	-	38,500	3,650	0.0	-
8- 5-83	155	18.0	0.45HDE	-	38,500	3,650	0.0	-
8- 8-83	156	4.0	0.45HDE	-	53,500	5,700	0.0	-
8- 9-83	157	4.0	0.45HDE	-	56,500	21,500	0.0	-
8- 9-83	158	4.0	0.45HDE	-	56,500	21,500	0.0	-
8-10-83	159	4.0	0.45HDE	-	56,500	40,000	0.0	-
8-10-83	160	4.0	0.45HDE	-	56,000	4,000	0.0	-
8-28-83	161	20.0	0.85HDE	-	9,150	350	0.0	-
9- 5-83	162	3.0	0.85HDE	-	12,800	20,000	0.0	-
11- 7-83	163	15.0	0.85HDE	-	8,233	4300	0.00	0.000
11- 8-83	164	16.0	0.85HDE	-	36,700	1150	0.00	0.000
11- 9-83	165	17.0	0.85HDE	-	56,300	1100	0.00	0.000
11-10-83	166	18.0	0.85HDE	-	51,000	1000	0.00	0.000
11-11-83	167	18.0	0.85HDE	-	-	-	0.00	0.000
11-14-83	168	18.0	0.85HDE	-	79,800	-	0.00	0.000
11-15-83	169	19.0	0.85HDE	-	23,400	-	0.00	0.000
11-16-83	170	20.0	0.85HDE	-	-	-	0.00	0.000
11-17-83	171	20.0	0.85HDE	-	10,500	600	0.00	0.000
11-18-83	172	20.0	0.85HDE	-	38,800	150	0.00	0.000
11-21-83	173	20.0	2.30HDE	-	18,200	1850	0.00	0.000
12-12-83	174	2.0	0.60CLP	-	14,700	1000	0.00	0.000
12-14-83	175	3.5	0.65CLP	-	5,500	3470	0.00	0.000
12-15-83	176	3.5	0.69CLP	-	3,300	300	0.00	0.000
12-16-83	177	4.0	0.77CLP	-	6,000	6550	0.00	0.000
12-19-83	178	4.0	0.78CLP	-	4,100	6850	0.00	0.000

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 4 of 12).

	CHEMICAL BASIN CONDITIONS								
	Alum (mg/1) as $Al_2(SO_4)_3 \cdot 14H_2O$ (10)	Velocity Gradient G (sec^{-1}) for Alum Basin (11)	Detention Time T (sec) Alum Basin (12)	GT for Alum Basin (13)	Polymer (mg/1) (14)	Brand of Polymer (15)	Velocity Gradient G (sec^{-1}) for Polymer Basin (16)	Detention Time T (sec) for Polymer Basin (17)	GT for Polymer Basin (18)
1	0.00	40.9	186.0	7607	0.00	-	57.2	186.0	10,639
1	0.00	40.9	186.0	7607	0.00	-	57.2	186.0	10,639
2	0.00	40.9	186.0	7607	0.00	-	57.2	186.0	10,639
2	0.00	40.9	186.0	7607	0.00	-	57.2	186.0	10,639
3	0.00	40.9	186.0	7607	4.60	8100N	57.2	186.0	10,639
3	0.00	40.9	186.0	7607	4.60	8100N	57.2	186.0	10,639
4	0.00	40.9	186.0	7607	0.31	8102N	57.2	186.0	10,639
4	0.00	40.9	186.0	7607	0.31	8102N	57.2	186.0	10,639
5	0.00	40.9	186.0	7607	1.77	8170N	57.2	186.0	10,639
5	0.00	40.9	186.0	7607	1.76	8170N	57.2	186.0	10,639
6	0.00	40.9	186.0	7607	2.02	8181N	57.2	186.0	10,639
6	0.00	40.9	186.0	7607	2.02	8181N	57.2	186.0	10,639
7	0.00	40.9	186.0	7607	2.46	8102N	57.2	186.0	10,639
7	0.00	40.9	186.0	7607	2.46	8102N	57.2	186.0	10,639
8	0.00	40.9	186.0	7607	1.10	8102N	57.2	186.0	10,639
8	0.00	40.9	186.0	7607	1.10	8102N	57.2	186.0	10,639
9	0.00	40.9	186.0	7607	1.93	8102N	57.2	186.0	10,639
10	0.00	40.9	186.0	7607	28.00	650N	57.2	186.0	10,639
11	23.38	40.9	186.0	7607	0.05	8181N	57.2	186.0	10,639
11	23.28	40.9	186.0	7607	0.05	8181N	57.2	186.0	10,639
12	16.90	40.9	186.0	7607	0.09	8181N	57.2	186.0	10,639
12	16.90	40.9	186.0	7607	0.09	8181N	57.2	186.0	10,639
13	14.05	40.9	186.0	7607	0.02	8181N	57.2	186.0	10,639
14	32.69	40.9	208.3	8519	-	-	57.2	208.3	11,914
15	12.96	40.9	95.3	3897	0.02	8102N	57.2	95.3	5,451
16	13.40	40.9	186.3	7607	0.05	8102N	57.2	186.0	10,639
17	19.37	40.9	186.3	7607	1.40	8102N	57.2	186.0	10,639
18	0.00	40.9	186.3	7607	21.55	572C	57.2	186.0	10,639
19	0.00	40.9	186.3	7607	16.00	572C	57.2	186.0	10,639
20	0.00	40.9	186.3	7607	0.80	572C	57.2	186.0	10,639
21	0.00	40.9	186.3	7607	16.30	752C	57.2	186.0	10,639
22	5.12	40.9	186.3	7607	6.40	572C	57.2	186.0	10,639
23	5.46	40.9	186.3	7607	0.62	572C	57.2	186.0	10,639
24	0.83	40.9	186.3	7607	0.32	572C	57.2	186.0	10,639
25	6.33	40.9	186.3	7607	0.77	572C	57.2	186.0	10,639
26	1.17	40.9	186.3	7607	0.30	572C	57.2	186.0	10,639
27	2.92	40.9	186.3	7607	0.27	573C	57.2	186.0	10,639
28	4.45	40.9	186.3	7607	0.17	573C	57.2	186.0	10,639
29	4.85	40.9	186.3	7607	0.25	573C	57.2	186.0	10,639
30	21.82	40.9	186.3	7607	0.79	573C	57.2	186.0	10,639
31	5.85	40.9	186.3	7607	0.45	572C	57.2	186.0	10,639
32	4.68	40.9	186.3	7607	1.70	572C	57.2	186.0	10,639
33	4.19	40.9	186.3	7607	1.59	572C	57.2	186.0	10,639
34	3.16	40.9	186.3	7607	1.38	572C	57.2	186.0	10,639
35	3.34	40.9	186.3	7607	2.10	572C	57.2	186.0	10,639
36	8.57	46.0	186.0	8566	4.09	572C	46.0	186.0	8,566
37	15.33	46.0	186.0	8566	8.33	572C	46.0	186.0	8,566
38	1.47	46.0	186.0	8566	1.97	572C	46.0	186.0	8,566
39	3.02	46.0	287.0	213,209	1.40	572C	46.0	278.0	13,209
40	5.57	32.9	278.0	9165	2.59	572C	46.0	278.0	12,790
41	15.07	33.4	282.5	9454	0.03	NP10	46.7	282.5	13,213
42	8.47	32.0	178.6	5716	1.45	572C	45.0	178.6	8,037
43	5.48	33.4	266.0	8901	2.81	572C	46.7	266.0	12,439
44	3.55	32.9	182.0	6001	3.85	572C	46.0	182.0	8,376
45	3.13	32.9	270.0	8903	1.47	572C	46.0	270.0	12,425
46	0.00	-	-	-	0.00	-	-	-	-
47	0.00	-	-	-	0.00	-	-	-	-
48	0.00	-	-	-	0.00	-	-	-	-
49	0.00	-	-	-	0.00	-	-	-	-
50	2.14	33.4	184.8	6184	0.90	572C	48.2	184.8	8,917
51	4.08	33.4	258.2	8639	1.68	572C	46.7	258.2	12,075
52	2.07	33.4	179.4	6003	1.17	572C	46.7	179.4	8,391
53	3.44	33.9	261.5	8880	2.13	572C	47.5	261.5	12,421
54	2.11	33.4	184.8	6184	$4.2x10^{-3}$	8102N	-	-	-

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 5 of 12).

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
55	3.16	34.9	273.1	9556	17.00	8102N	-	-	-
56	5.30	33.4	186.2	6231	0.30	8102N	-	-	-
57	5.07	33.4	267.1	8940	2.17	8102N	-	-	-
58	2.47	33.2	180.7	6001	1.47	572C	46.3	180.7	8,383
59									
60	13.7	34.4	256.2	8826	0.50	572C	48.2	256.0	12,354
61	15.97	38.6	180.2	6963	0.73	573C	54.0	180.2	9,737
62	16.63	33.4	180.2	6029	0.90	573C	46.7	180.2	8,428
63	18.52	32.9	196.2	6534	0.50	573C	46.0	198.2	9,119
64	28.02	32.9	187.6	6185	1.00	573C	46.0	187.6	8,631
65	18.52	33.2	180.7	6002	0.44	573C	46.3	180.7	8,383
66	17.17	160.0	184.0	29,440	0.52	573C	160.0	184.0	29,440
67	17.12	160.0	184.0	29,440	0.26	573C	160.0	184.0	29,440
68	12.07	160.0	184.8	29,570	1.61	573C	160.0	184.8	29,570
69	14.96	160.0	267.1	42,749	1.08	573C	160.0	267.2	42,749
70	7.64	160.0	273.1	43,696	1.33	573C	160.0	273.1	43,696
71	15.00	617.0	178.6	110,196	1.31	573C	617.0	178.6	110,196
72	16.62	446.0	178.1	79,432	1.30	573C	446.0	178.6	79,432
73	24.60	300.0	285.8	85,740	1.22	573C	300.0	285.8	85,740
74	13.15	300.0	281.8	84,566	1.37	573C	300.0	281.8	84,566
75	12.70	300.0	273.1	81,935	2.00	573C	300.0	273.1	81,935
76	0.00	- .0	-	-	-	-	-	-	-
77	0.00	- .0	-	-	-	-	-	-	-
78	0.00	- .0	-	-	-	-	-	-	-
79	0.00	- .0	-	-	-	-	-	-	-
80	5.56	300.0	183.4	55,031	0.74	572C	300.0	183.4	55,031
81	6.77	300.0	181.5	54,462	0.80	572C	300.0	181.5	54,462
82	8.82	300.0	270.1	81,035	0.55	572C	300.0	270.1	81,035
83	75.63	300.0	270.1	81,035	11.00	572C	300.0	270.1	81,035
84	12.60	300.0	270.1	81,035	1.97	572C	300.0	270.1	81,035
85A	13.03	300.0	279.1	83,797	1.31	572C	300.0	279.1	83,797
85B	13.00	300.0	279.1	83,797	1.31	572C	300.0	279.1	83,797
86A	15.64	300.0	186.2	55,865	1.28	572C	300.0	186.2	55,865
86B	15.64	300.0	186.2	55,865	1.28	572C	300.0	186.2	55,865
87A	14.77	300.0	186.2	55,865	2.19	572C	300.0	186.2	55,865
87B	14.77	300.0	186.2	53,865	2.19	572C	300.0	186.2	55,865
88A	17.55	300.0	258.7	77,623	4.42	573C	300.0	258.7	77,623
88B	24.14	300.0	258.7	77,623	4.42	573C	300.0	258.7	77,623
89A	16.57	300.0	273.1	81,935	2.0	573C	300.0	273.1	81,935
89B	16.57	300.0	273.1	81,935	2.0	573C	300.0	273.1	81,935
90A	22.69	300.0	180.7	54,222	1.76	573C	300.0	180.7	54,222
90B	22.69	300.0	180.7	54,222	1.76	573C	300.0	180.7	54,222
91A	15.10	300.0	180.7	54,222	3.2	573C	300.0	180.7	54,222
91B	15.10	300.0	180.7	54,222	3.2	573C	300.0	180.7	54,222
92A	2.85	300.0	273.1	81,935	3.36	573C	300.0	273.1	81,935
92B	2.85	300.0	273.1	81,935	3.56	573C	300.0	273.1	81,935
93A	5.30	300.0	256.0	76,814	3.33	573C	300.0	256.0	76,814
93B	5.30	300.0	256.0	76,814	2.66	573C	300.0	256.0	76,814
94	0.00	-	-	-	-	-	-	-	-
95	0.00	-	-	-	-	-	-	-	-
96	0.00	-	-	-	-	-	-	-	-
97	0.00	-	-	-	-	-	-	-	-
98	0.00	-	-	-	8.79	573C	237.1	186.2	44,159
99	0.00	-	-	-	7.46	573C	237.1	183.4	43,493
100	0.00	-	-	-	7.51	572C	237.1	184.5	43,754
101A	9.70	237.1	186.2	44,159	0.00	-	-	-	-
101B	9.70	237.1	186.2	44,159	0.00	-	-	-	-
102A	7.70	237.1	183.4	43,493	0.00	-	-	-	-
102B	7.70	237.1	183.4	43,493	0.00	-	-	-	-
103	17.20	237.1	183.4	43,494	1.34	573C	237.1	183.4	43,494
104A	9.60	237.1	183.4	43,494	1.5	573C	237.1	183.4	43,494
104B	13.40	237.1	183.4	43,494	0.6	573C	237.1	183.4	43,494
105	11.50	237.1	183.4	43,494	0.82	573C	237.1	183.4	43,494
106	0.00	-	-	-	0.49	8102N	-	-	-
107A	11.34	237.1	180.7	42,853	0.47	572C	237.1	180.7	42,853
107B	11.34	237.1	180.7	42,857	0.47	572C	237.1	180.7	42,853
108	12.30	237.1	180.7	42,837	0.49	572C	237.1	180.7	42,853
109	17.70	237.1	178.1	42,232	0.87	572C	237.1	178.1	42,232
110	18.64	237.1	178.1	42,232	0.8	572C	237.1	178.1	42,232
111	18.59	298.1	148.1	44,152	0.96	572C	298.1	148.1	44,152
112	18.50	237.1	186.2	44,152	0.95	572C	237.1	186.2	44,152
113	18.50	150.1	294.0	44,152	0.98	572C	150.1	294.0	44,152

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 6 of 12).

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
114	23.24	59.6	740.3	44,152	1.2	572C	59.6	740.3	44,152
115	34.50	294.6	149.9	44,152	1.6	572C	294.6	149.9	44,152
116	33.30	152.7	289.1	44,152	3.0	572C	152.7	289.1	44,152
117	37.30	235.3	187.6	44,152	1.6	572C	235.3	187.6	44,152
118	23.69	68.3	646.8	44,152	1.42	572C	68.3	646.8	44,152
119	0	-	-	-	0.00	-	-	-	-
120	0	-	-	-	0.00	-	-	-	-
121	0	-	-	-	0.00	-	-	-	-
122	0	-	-	-	0.00	-	-	-	-
123	0	-	-	-	0.00	-	-	-	-
124	0	-	-	-	0.00	-	-	-	-
125	69.00	180	296.0	53,307	14.5	572C	180.0	296.0	53,307
126A	32.53	180	296.0	53,307	12.77	572C	180.0	296.0	53,307
126B	32.50	180	296.0	53,307	12.77	572C	180.0	296.0	53,307
127A	32.50	217	296.0	64,199	5.06	572C	217.0	296.0	64,199
127B	32.50	217	296.0	64,199	5.06	572C	217.0	296.0	64,199
128A	32.50	186	296.0	55,056	5.06	572C	186.0	296.0	55,056
128B	32.50	186	296.0	55,056	5.06	572C	186.0	296.0	55,056
129	32.50	180	296.0	55,307	5.06	572C	180.0	296.0	53,307
130	32.50	197	296.0	58,284	5.06	572C	197.0	296.0	58,284
131A	58.80	217	296.0	64,199	0.00	-	-	-	-
131B	0	-	-	-	19.30	572C	217.0	296.0	64,199
132	0	-	-	-	19.30	572C	186.0	296.0	55,056
133	0.00	-	-	-	8.15	572C	241	267.1	64,371
134	0.00	-	-	-	0.00	-	-	-	-
135	-	237	267.1	63,303	2.48	572C	237	267.1	63,303
136	2.08	241	267.1	64,371	0.00	-	-	-	-
137	3.08	241	267.1	64,371	4.11	572C	241	267.1	64,371
138	3.64	241	267.1	64,371	4.13	572C	241	267.1	64,371
139	3.64	241	267.1	64,371	4.30	572C	241	267.1	64,371
140	0.00	-	-	-	0.00	-	-	-	-
141	3.47	282	267.1	75,322	4.52	572C	282	267.1	75,322
142	3.69	280	267.1	74,788	4.36	572C	280	267.1	74,788
143	4.56	280	267.1	74,788	3.64	572C	280	267.1	74,788
144	0.00	-	-	-	1.97	572C	280	267.1	74,788
145	2.46	280	267.1	74,788	0.00	-	-	-	-
146	1.45	240	270.1	64,824	0.35	572C	240	270.1	64,824
147	1.45	240	270.1	64,824	0.35	572C	240	270.1	64,824
148	0.64	240	279.1	66,984	0.62	572C	240	279.1	66,984
149	0.61	240	285.8	68,592	0.65	572C	240	285.8	68,592
150	0.87	188	248.2	46,661	0.00	-	-	-	-
151	0.00	-	-	-	0.42	572C	188	248.2	46,661
152	0.67	188	248.2	46,661	1.85	572C	188	248.2	46,661
153	0.00	-	-	-	0.00	-	-	-	-
154	0.85	188	248.2	46,661	0.47	572C	188	248.2	46,661
155	1.41	188	248.2	46,661	0.47	572C	188	248.2	46,661
156	1.41	159	248.2	39,464	0.97	572C	159	248.2	39,464
157	1.41	159	248.2	39,464	1.01	572C	159	248.2	39,464
158	0.85	159	248.2	39,464	0.48	572C	159	248.2	39,464
159	0.00	-	-	-	0.40	572C	159	248.2	39,464
160	0.67	159	248.2	39,464	1.82	572C	159	248.2	39,464
161	0.97	188	284.4	53,485	2.31	572C	188	284.4	53,485
162	0.97	159	284.4	45,220	2.31	572C	159	284.2	45,220
163	0.00	-	-	-	0.00	-	-	-	-
164	15.25	217.0	285.8	62,023	0.00	573C	217.0	285.8	62,023
165	0.00	-	-	-	0.48	573C	217.0	285.8	62,023
166	17.04	220.0	285.8	62,881	0.16	573C	220.8	285.8	62,881
167	14.95	220.0	285.8	62,881	2.50	573C	220.0	285.8	62,881
168	7.48	220.0	285.8	62,881	2.02	573C	220.0	285.8	62,881
169	15.55	220.0	285.8	62,881	0.72	573C	220.0	285.8	62,881
170	9.27	180.0	285.8	52,877	0.65	573C	180.0	285.8	52,877
171	22.05	180.0	285.8	52,877	-	573C	180.0	285.8	52,877
172	26.01	180.0	285.8	52,877	0.14	573C	180.0	285.8	52,877
173	0.00	-	-	-	0.00	-	-	-	-
174	0.00	-	-	-	0.00	-	-	-	-
175	0.00	-	-	-	2.6	573C	159.0	280.0	44,615
176	19.18	159.0	280.0	44615	1.57	573C	159.0	280.0	44,615
177	34.05	159.0	280.0	44615	0.46	573C	159.0	280.0	44,615
178	17.61	159.0	280.0	44615	0.57	573C	159.0	280.0	44,615

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 7 of 12).

FILTER CONDITIONS

	Filtration Rate (cm/min) (19)	Diameter of Filter (cm) (21)	Media (21)	Temperature (°C) (22)	Differential Pressure (cm Hg) (23)	Volume of Filtered Water (liter) (24)	Length of Run (hr) (25)
1	32.80	5.08	dual	10.0	10.0	308.0	7.78
1	8.14	10.16	dual	10.0	2.4	308.0	7.78
2	8.22	10.16	single	9.5	5.3	200.0	5.00
2	31.47	5.08	single	8.0	25.0	191.0	5.00
3	30.11	5.08	single	13.0	14.0	92.0	4.00
3	8.10	10.16	dual	14.0	5.0	187.0	4.00
4	8.70	10.16	single	18.0	20.0	116.0	3.50
4	22.80	5.08	dual	17.5	17.0	111.0	4.00
5	43.92	5.08	single	15.5	1.3	80.0	1.50
5	11.80	10.16	dual	15.5	1.3	22.0	1.50
6	9.49	10.16	single	16.5	4.6	105.0	2.50
6	30.30	5.08	dual	15.0	9.1	120.0	2.50
7	7.80	10.16	dual	16.0	2.2	57.0	1.50
7	29.12	5.08	single	16.0	22.5	53.0	1.50
8	9.60	10.16	single	15.5	8.0	140.0	3.00
8	29.90	5.08	single	15.5	15.0	109.0	3.00
9	8.60	10.16	single	14.0	14.0	147.0	3.50
10	34.50	5.08	dual	16.0	9.2	42.0	1.00
11	8.07	10.16	single	19.5	4.7	138.0	3.50
11	24.90	5.08	dual	18.5	9.1	106.0	3.50
12	6.53	10.16	single	18.0	24.0	127.0	4.00
12	30.10	5.08	dual	17.3	17.0	146.0	4.00
13	29.10	5.08	dual	19.0	13.7	- .0	4.75
14	29.10	5.08	dual	17.5	9.1	124.0	3.50
15	15.50	5.28	single	16.5	15.5	271.0	3.50
16	32.91	10.16	dual	17.3	9.2	100.0	2.50
17	9.00	10.16	dual	16.5	3.8	131.0	3.00
18	8.24	10.16	single	20.0	4.4	220.0	5.50
19	32.90	5.08	dual	20.1	8.8	80.0	2.00
20	8.59	10.16	dual	21.0	2.1	188.0	4.50
21	34.40	5.08	single	21.0	17.0	230.0	5.50
22	8.20	10.16	single	21.5	5.1	180.0	4.50
23	32.56	5.08	dual	18.0	12.0	159.0	4.50
24	8.20	10.16	dual	19.0	2.2	120.0	3.00
25	32.56	5.08	single	20.0	20.0	119.0	3.00
26	8.14	10.16	single	20.5	6.4	198.0	5.00
27	32.56	5.08	dual	20.5	10.0	109.0	2.75
28	8.20	10.16	dual	20.5	2.8	160.0	4.00
29	32.07	5.08	single	20.0	22.5	182.0	4.66
30	8.14	10.16	single	13.5	13.0	218.0	5.50
31	8.14	10.16	single	17.5	6.9	132.0	3.33
32	32.56	5.08	dual	18.5	14.0	139.0	3.50
33	8.14	10.16	dual	19.0	3.1	89.0	2.25
34	32.56	5.08	single	19.5	21.0	80.0	2.00
35	8.20	10.16	single	19.0	9.0	106.0	2.67
36	8.14	10.16	single	7.5	9.0	178.2	4.50
37	32.45	5.08	dual	5.2	16.3	598.0	4.00
38	8.14	10.16	dual	7.0	5.1	178.2	4.50
39	21.20	5.08	single	9.5	18.5	90.0	3.50
40	21.80	5.08	dual	8.0	11.7	97.2	3.67
41	5.37	10.16	single	8.0	20.0	143.5	5.50
42	8.48	10.16	single	8.0	9.4	103.2	2.50
43	22.80	5.08	dual	10.0	11.4	27.6	1.00
44	8.32	10.16	dual	7.0	4.2	89.1	2.20
45	22.45	5.08	single	8.5	23.5	56.9	2.08
46	8.47	10.16	single	7.0	6.4	59.8	1.45
47	22.59	5.08	dual	9.0	9.1	27.4	1.00
48	8.26	10.16	dual	7.0	4.2	51.6	1.28
49	22.20	5.08	single	10.0	15.0	40.5	1.50
50	8.20	10.16	single	7.0	9.2	109.7	2.75
51	23.48	5.08	dual	6.0	10.6	115.1	4.00
52	8.45	10.16	dual	7.0	5.0	102.7	2.50
53	23.19	5.08	single	9.5	18.7	65.8	2.33
54	8.20	10.16	single	7.0	6.5	113.0	2.83

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 8 of 12).

	(19)	(21)	(21)	(22)	(23)	(24)	(25)
55	22.20	5.08	dual	7.0	10.4	54.0	2.00
56	8.14	10.16	dual	8.0	3.5	103.0	2.60
57	22.69	5.08	single	9.5	16.8	47.0	1.70
58	8.20	10.16	single	7.0	9.0	83.0	2.03
59							
60	23.70	5.08	single	7.0	18.1	108.0	3.00
61	8.41	10.16	dual		15.5	163.0	4.00
62	8.41	10.16	dual	7.0	6.1	193.7	4.73
63	30.60	5.08	single	8.5	37.5	18.6	0.50
64	32.31	5.08	dual	6.5	19.1	59.0	1.50
65	8.39	10.16	single	7.0	39.0	71.4	1.75
66	8.24	10.16	single	6.5	9.4	114.0	2.75
67	8.26	10.16	dual	5.5	5.0	160.8	4.00
68	32.80	5.08	dual	4.5	19.0	80.0	2.00
69	22.69	5.08	dual	4.0	4.1	103.5	3.45
70	22.20	5.08	dual	5.0	25.9	31.5	1.16
71	8.49	10.16	single	5.5	9.8	130.7	2.16
72	8.51	10.16	dual	5.0	5.7	182.8	4.41
73	21.21	5.08	dual	6.0	12.2	103.2	4.00
74	21.50	5.08	single	6.0	22.4	65.2	2.50
75	22.20	5.08	dual	5.0	11.3	117.0	4.33
76	8.14	10.16	single	5.0	6.9	39.6	1.00
77	8.14	10.16	dual	5.0	4.0	33.0	0.83
78	20.72	5.08	single	7.0	15.7	29.4	1.16
79	20.72	5.08	dual	6.5	0.4	25.5	1.00
80	8.26	10.16	single	5.0	8.5	137.3	3.41
81	8.35	10.16	dual	4.0	5.4	206.5	5.08
82	22.45	5.08	dual	4.0	11.6	132.0	4.83
83	22.45	5.08	single	5.0	20.0	27.3	1.00
84	22.45	5.08	dual	7.0	16.1	40.9	1.50
85A	21.70	5.08	single	7.0	20.0	13.2	0.50
85B	21.70	5.08	single	7.0	23.6	26.4	1.00
86A	8.14	10.16	single	5.5	7.0	19.8	0.50
86B	8.14	10.16	single	5.5	11.6	89.1	2.25
87A	8.14	10.16	dual	4.0	4.6	19.8	.50
87B	8.14	10.16	dual	4.0	5.1	77.2	1.95
88A	23.44	5.08	dual	8.0	10.2	14.2	0.50
88B	23.44	5.08	dual	6.0	-	3.8	0.13
89A	22.20	5.08	single	8.0	17.8	6.7	0.25
89B	22.20	5.08	single	8.0	19.9	6.7	0.25
90A	8.38	10.16	single	6.0	7.2	10.2	0.25
90B	8.38	10.16	single	6.0	20.5	68.0	1.66
91A	8.38	10.16	dual	5.5	3.9	10.2	0.20
91B	8.38	10.16	dual	5.5	4.2	20.4	0.50
92A	22.20	5.08	dual	6.0	14.3	31.5	1.16
92B	22.20	5.08	dual	6.0	16.5	40.5	1.50
93A	23.68	5.08	single	12.0	17.9	12.0	0.20
93B	23.68	5.08	single	9.0	27.1	24.0	0.83
94	8.14	10.16	single	7.0	8.0	27.0	0.68
95	8.14	10.16	dual	5.5	3.4	29.7	0.75
96	21.46	5.08	single	6.0	18.0	10.0	0.38
97	21.46	5.08	dual	5.0	9.1	8.7	0.33
98	8.14	10.16	single	6.0	7.9	151.8	3.83
99	8.26	10.16	dual	5.5	3.0	90.5	2.25
100	8.21	10.16	single	6.0	6.5	80.0	2.08
101A	8.14	10.16	single	8.0	6.0	9.2	0.23
101B	8.14	10.16	single	8.0	10.0	63.4	1.6
102A	8.26	10.16	dual	5.0	3.4	2.01	0.05
102B	8.26	10.16	dual	5.0	3.0	20.8	0.52
103	8.26	10.16	dual	5.0	4.4	244.6	6.08
104A	8.26	10.16	dual	5.0	2.6	153.4	3.82
104B	8.26	10.16	dual	5.0	3.0	192.2	4.8
105	8.26	10.16	dual	14.0	2.0	20.1	0.50
106	8.47	10.16	dual	5.0	2.8	199.2	4.83
107A	8.38	10.16	dual	4.0	3.0	10.2	0.25
107B	8.38	10.16	dual	4.0	3.4	87.0	2.13
108	8.38	10.16	dual	7.0	2.7	122.4	3.00
109	8.51	10.16	dual	10.0	2.1	25.5	0.62
110	8.51	10.16	dual	4.0	3.1	20.7	0.50
111	40.95	5.08	dual	5.5	19.2	49.8	1.00
112	32.56	5.08	dual	5.0	15.0	79.2	2.00
113	20.60	5.08	dual	6.0	7.8	37.6	1.50

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 9 of 12).

	(19)	(21)	(21)	(22)	(23)	(24)	(25)
114	7.80	5.08	dual	8.0	3.5	10.9	1.10
115	40.40	5.08	dual	6.0	19.0	62.3	1.26
116	20.96	5.08	dual	9.0	9.5	27.6	1.08
117	32.30	5.08	dual	6.0	17.5	61.6	1.56
118	9.37	5.08	dual	11.0	4.0	38.0	3.33
119	41.40	5.08	dual	4.0	17.9	36.1	0.71
120	32.00	5.08	dual	4.0	13.5	26.0	0.66
121	20.70	5.08	dual	4.0	8.8	16.8	0.66
122	9.60	5.08	dual	6.0	4.0	7.8	0.66
123	40.20	5.08	dual	7.0	20.6	33.4	0.68
124	32.56	5.08	dual	6.0	18.5	26.4	0.66
125	20.47	5.08	dual	4.0	13.7	132.3	5.32
126A	20.47	5.08	dual	4.0	9.5	31.1	1.25
126B	20.47	5.08	dual	4.0	9.3	41.5	1.66
127A	20.47	5.08	dual	17.0	6.8	18.7	0.75
127B	20.47	5.08	dual	17.0	7.2	18.7	0.75
128A	20.47	5.08	dual	7.0	10.3	18.7	0.75
128B	20.47	5.08	dual	7.0	9.2	18.7	0.75
129	20.47	5.08	dual	7.0	9.3	18.7	0.75
130	20.47	5.08	dual	12.0	8.0	18.7	0.75
131A	20.47	5.08	dual	16.5	7.0	18.7	0.75
131B	20.47	5.08	dual	15.5	8.1	18.7	0.75
132	20.47	5.08	dual	7.0	9.8	18.7	0.75
133	22.69	5.08	dual	7.5	4.5	17.9	0.65
134	22.69	5.08	dual	7.0	9.0	24.4	0.88
135	22.69	5.08	dual	3.5	10.5	65.3	2.37
136	22.69	5.08	dual	6.0	9.8	20.7	0.75
137	22.69	5.08	dual	4.5	10.7	20.7	0.75
138	22.69	5.08	dual	4.5	10.9	27.6	1.00
139	22.69	5.08	dual	6.0	10.4	20.7	0.75
140	22.69	5.08	dual	14.0	7.1	27.6	1.00
141	22.69	5.08	dual	14.0	8.1	34.5	1.25
142	22.69	5.08	dual	14.5	7.6	20.7	0.75
143	22.69	5.08	dual	14.5	7.8	20.7	0.75
144	22.69	5.08	dual	15.5	7.0	20.7	0.75
145	22.69	5.08	dual	15.5	7.1	20.7	0.75
146	22.45	5.08	dual	7.0	11.1	71.3	2.58
147	22.45	5.08	dual	8.0	11.5	55.2	2.00
148	21.70	5.08	dual	6.0	12.1	132.0	5.00
149	22.22	5.08	dual	7.0	13.2	132.0	5.00
150	22.42	5.08	dual	17.0	8.1	29.7	1.00
151	22.42	5.08	dual	17.0	7.4	29.7	1.00
152	22.42	5.08	dual	17.0	8.0	29.7	1.00
153	22.42	5.08	dual	17.0	7.0	29.7	1.00
154	22.42	5.08	dual	18.0	7.4	29.7	1.00
155	22.42	5.08	dual	18.0	8.5	29.7	1.00
156	22.42	5.08	dual	7.0	10.0	29.7	1.00
157	22.42	5.08	dual	7.0	10.5	29.7	1.00
158	22.42	5.08	dual	7.0	11.6	29.7	1.00
159	22.42	5.08	dual	7.0	10.4	29.7	1.00
160	24.40	5.08	dual	6.5	11.5	29.7	1.00
161	21.30	5.08	dual	19.5	8.2	35.0	1.35
162	21.30	5.08	dual	4.0	10.0	39.0	1.50
163	21.2	5.08	dual	14.5	6.7	25.8	1.00
164	21.2	5.08	dual	16.0	6.6	25.8	1.00
165	21.2	5.08	dual	17.0	6.7	25.8	1.00
166	21.2	5.08	dual	17.5	6.9	51.6	2.00
167	21.2	5.08	dual	19.0	7.5	103.2	4.00
168	21.2	5.08	dual	19.0	8.2	129.0	5.00
169	21.2	5.08	dual	19.0	6.6	25.8	1.00
170	21.2	5.08	dual	2.5	9.0	25.8	1.00
171	21.2	5.08	dual	2.5	10.2	51.6	2.00
172	21.2	5.08	dual	2.5	11.7	103.2	4.00
173	21.2	5.08	dual	3.0	8.0	25.8	1.00
174	21.2	5.08	dual	4.5	9.4	52.0	2.00
175	21.2	5.08	dual	2.0	9.6	52.0	2.00
176	21.2	5.08	dual	3.0	11.0	52.0	2.00
177	21.2	5.08	dual	2.5	11.4	52.0	2.00
178	21.2	5.08	dual	3.0	11.6	59.13	2.25

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 10 of 12).

+	FILTER EFFLUENT DATA										
	Turbidity (NTU) (26)	% Removal of Turbidity (27)	Particle Count (No./10 ml) 2.52 - 50.8 µm (28)	% Removal of Particle Count (29)	Standard Plate Count (No./ml) (30)	% Removal of Standard Plate Count (31)	Total Coliform (No./100 ml) (32)	% Removal of Total Coliform (33)	Giardia Cysts (cysts/L) (34)	% Removal of Giardia Cysts (35)	Volume Filter for Giardia Cyst Sample (36)
1	5.00	16.67	-	-	-	-	-	-	0.000	0.00	0.0
1	4.80	20.00	-	-	-	-	-	-	0.000	0.00	0.0
2	3.60	0.00	22902	69.16	30,250	48.73	9,600	8.57	0.000	0.00	0.0
2	3.60	0.00	19802	73.34	33,000	44.00	10,000	4.76	0.000	0.00	0.0
3	2.50	16.67	6465	65.78	-	-	79	65.65	0.000	0.00	0.0
3	3.80	-26.67	9116	51.70	-	-	81	64.78	0.000	0.00	0.0
4	0.43	88.68	3290	90.70	9,000	90.72	10,000	0.00	0.000	0.00	0.0
4	0.32	91.58	1776	94.98	1,000	98.97	10,000	0.00	0.000	0.00	0.0
5	3.00	18.92	11663	67.76	2,800	92.22	-	-	0.000	0.00	0.0
5	2.10	43.24	11549	68.08	5,800	83.89	-	-	0.000	0.00	0.0
6	1.30	62.86	13860	63.78	-	-	-	-	0.000	0.00	0.0
6	2.30	34.29	10495	72.81	-	-	-	-	0.000	0.00	0.0
7	0.50	84.37	17191	62.00	1,620	93.60	40,000	88.57	0.000	0.00	0.0
7	0.34	89.38	24518	45.81	940	96.28	60,000	82.86	0.000	0.00	0.0
8	0.23	93.03	3155	92.47	1,360	94.96	26,000	85.56	0.000	0.00	0.0
8	0.33	90.00	7221	82.77	880	96.70	25,000	86.11	0.000	0.00	0.0
9	0.22	93.33	5857	89.05	17,600	95.45	5,500	89.81	0.000	0.00	0.0
10	3.20	3.03	-	-	7,250	95.51	5,900	3.28	0.000	0.00	0.0
11	2.80	20.00	-	-	37,667	70.30	3,500	45.31	0.000	0.00	0.0
11	2.40	27.27	-	-	16,350	87.10	4,600	28.13	0.000	0.00	0.0
12	0.44	86.67	783	88.87	3,500	87.50	200	84.00	0.000	0.00	0.0
12	0.24	92.73	652	90.73	3,600	87.10	<1	>99.00	0.000	0.00	0.0
13	0.30	92.86	24518	88.85	9,800	34.62	50	96.87	0.000	0.00	0.0
14	0.08	98.22	12262	90.90	1,050	90.70	<1	>99.95	0.000	0.00	0.0
15	0.08	97.65	15741	78.60	150	96.81	8	99.00	0.000	0.00	0.0
16	0.04	98.92	200	99.70	620	96.90	1	98.80	0.000	0.00	0.0
17	0.70	81.08	-	-	-	-	-	-	0.000	0.00	0.0
18	0.25	58.33	240	96.95	146	97.46	0	100.00	0.000	0.00	0.0
19	0.54	53.45	-	-	-	-	-	-	0.000	0.00	0.0
20	0.54	-31.71	112	99.95	39,300	91.50	<1	>99.00	0.000	0.00	0.0
21	0.44	-4.76	50896	12.60	153,000	61.60	1	98.57	0.000	0.00	0.0
22	0.05	90.48	3760	93.50	5,000	98.70	<1	>98.50	0.000	0.00	0.0
23	0.04	95.60	164	99.40	950	98.30	<1	>99.50	0.000	0.00	0.0
24	0.04	95.60	1090	91.00	1,380	99.50	<1	>99.00	0.000	0.00	0.0
25	0.04	95.60	668	97.50	1,485	99.50	<1	>99.00	0.000	0.00	0.0
26	0.03	76.92	-	-	-	-	-	-	0.000	0.00	0.0
27	0.05	77.27	-	-	295	99.90	<1	>99.09	0.000	0.00	0.0
28	0.03	81.25	-	-	1,040	74.90	<1	>98.00	0.000	0.00	0.0
29	0.06	62.50	-	-	660	84.20	<1	>98.00	0.000	0.00	0.0
30	0.08	52.94	-	-	226	-7.60	<1	>99.00	0.000	0.00	0.0
31	0.09	59.09	694	81.80	9,000	63.27	1	98.95	0.000	0.00	0.0
32	0.03	86.36	41	99.62	2,630	99.90	9	98.60	0.000	0.00	0.0
33	0.04	81.82	4	99.92	2,055	93.70	4	99.38	0.000	0.00	0.0
34	0.05	77.27	3	99.95	4,643	85.71	27	95.80	0.000	0.00	0.0
35	0.04	87.10	494	96.68	-	-	-	-	0.000	0.00	0.0
36	0.05	81.48	160	98.05	910	95.75	-	-	-	-	-
37	0.03	87.21	-	-	-	-	-	-	-	-	-
38	0.03	84.21	10	99.92	1,047	94.56	<0.5	99.90	-	-	-
39	0.03	84.21	423	96.65	8,250	42.23	<1.0	>99.90	-	-	-
40	0.04	78.95	77	99.39	390	85.82	2.5	96.15	-	-	-
41	0.05	80.00	-	-	-	-	-	-	-	-	-
42	0.09	85.94	-	-	-	-	-	-	0.000	100.00	43.3
43	0.06	90.63	-	-	-	-	-	-	0.000	100.00	27.4
44	0.08	89.47	-	-	-	-	-	-	0.000	100.00	18.7
45	0.07	90.79	-	-	-	-	-	-	1.932	91.69	20.7
46	0.16	27.27	711	85.78	4,000	-51.25	3450.0	13.75	66.163	74.55	30.2
47	0.38	-72.73	55	98.90	3,250	-66.67	3000.0	25.00	9.704	96.27	12.3
48	0.26	-18.18	291	94.18	3,800	-108.20	800.0	38.46	0.000	100.00	33.5
49	0.33	-13.79	71	98.58	2,900	20.55	520.0	60.00	0.000	100.00	16.6
50	0.04	88.89	400	98.55	2,250	82.28	<1.0	>99.90	2.506	97.77	39.9
51	0.05	86.11	368	98.92	890	87.51	14.0	80.00	0.000	100.00	6.4
52	0.03	91.67	250	99.18	745	95.55	<1.0	>99.90	0.000	100.00	15.0
53	0.08	82.61	2313	93.82	2,530	-	<1.0	>99.90	0.000	100.0	10.2
54	0.57	-38.60	-	-	1,750	43.05	1040	29.50	16.660	95.10	12.0

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 11 of 12).

	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)
55	0.60	33.30	2092	95.36	1,240	95.85	4.5	98.50	0.000	100.00	9.0
56	0.39	17.02	730	98.85	5,800	94.93	2.5	98.70	15.150	91.09	13.2
57	0.12	74.02	809	98.72	6,100	79.52	<1.0	>99.90	0.000	100.00	10.2
58	0.03	94.00	2130	97.93	8,750	89.61	<1.0	>99.90	28.900	87.13	19.0
59											
60	0.07	79.41	-	-	-	-	-	-	-	-	-
61	0.04	99.05	34	>99.90	3,005	92.29	<1.0	>99.90	-	-	143.2
62	0.05	98.81	2394	99.65	2,340	98.55	<1.0	>99.90	0.000	0.00	143.2
63	0.29	93.10	-	-	-	-	-	-	-	-	-
64	0.32	92.38	269415	71.99	3,000	>98.47	<1.0	>99.90	0.000	0.00	3.2
65	0.05	98.84	5132	99.47	1,250	88.99	-	-	0.000	0.00	14.9
66	0.05	88.89	291	99.27	410	91.14	<1	>99.90	<1.000	>99.90	140.2
67	0.05	90.20	88	99.78	173	87.37	<1	>99.90	<1.000	>99.90	120.6
68	0.91	-71.7	182,894	-301.00	1,100	17.29	<1	>99.90	25.060	94.25	17.9
69	0.14	73.58	110,558	-142.42	1,280	78.84	<0.5	>99.90	<1.000	>99.00	4.6
70	0.06	88.68	8237	81.94	97	98.40	<0.5	>99.50	3.220	99.30	34.2
71	0.04	95.83	161	99.89	1,900	98.92	<0.5	>99.90	<1.000	>99.90	61.9
72	0.05	94.95	13	99.99	250	99.83	<1	>99.90	<1.000	>99.90	127.6
73	1.27	-15.45	-	-	30,000	18.00	-	-	-	-	-
74	0.08	93.85	24,232	83.05	595	98.34	<1	>99.99	2.158	99.48	31.8
75	0.52	60.90	-	-	-	-	-	-	13.070	95.97	7.6
76	0.36	23.4	123	98.86	-	-	-	-	11.110	94.44	33.0
77	0.4	14.8	<10	99.92	-	-	-	-	-	-	24.4
78	0.48	-2.1	-	-	-	-	-	-	-	-	25.2
79	0.48	-2.1	496	95.42	-	-	-	-	-	-	22.1
80	0.08	82.9	<10	99.84	710	94.32	<1	>99.90	-		62.3
81	0.07	85.4	240	98.34	161	97.73	<1	>99.90	-	-	90.0
82	0.23	61.0	<10	99.00	127	99.58	<1	>99.90	-	-	20.4
83	0.08	86.4	<10	99.00	-	-	-	-	-	-	30.0
84	1.05	52.2	-	-	-	-	-	-	-	-	-
85A	0.09	95.91	873	99.25	530	96.97	88	99.96	<1.000	>99.90	13.2
85B	0.12	94.55	27,800	75.96	870	95.03	2870	98.57	5.681	>99.81	26.4
86A	0.12	95.20	1117	99.47	300	99.00	20	99.80	<1.000	>99.90	19.8
86B	0.06	97.6	361	99.80	300	99.00	33	96.67	<1.000	>99.90	91.7
87A	0.10	96.00	33,651	91.40	1210	99.37	125	99.48	0.488	99.97	19.8
87B	0.07	97.2	361	99.91	640	99.67	310	99.69	0.336	99.98	106.9
88A	0.22	94.21	1454	99.70	12,200	95.93	1000	99.90	2.185	99.91	14.2
88B	0.88	76.84	20,890	56.66	22,300	92.57	1000	99.90	26.315	98.84	3.8
89A	0.12	96.84	615	99.92	6200	94.07	150,000	98.81	1.481	99.94	13.5
89B	0.11	97.11	57,277	92.71	6700	98.99	276,000	97.81	2.614	99.90	49.9
90A	0.1	95.45	<10	99.90	-	-	13	99.97	<1.000	>99.90	20.4
90B	0.08	96.36	<10	99.90	-	-	33	99.95	<1.000	>99.90	70.0
91A	0.12	95.00	<10	99.90	76,500	72.43	34	99.86	<1.000	>99.90	20.4
91B	0.08	96.67	<10	99.90	37,500	86.44	63	94.78	<1.000	>99.90	68.0
92A	0.47	95.10	-	-	-	-	-	-	-	-	-
92B	0.73	92.40	-	-	-	-	-	-	-	-	-
93A	0.45	95.31	-	-	-	-	-	-	-	-	-
93B	0.51	94.69	-	-	-	-	-	-	-	-	-
94	1.77	-1.12	14,289	81.07	87,000	14.29	2,000	90.00	58.213	92.22	19.8
95	1.50	11.76	18,292	75.76	87,000	14.29	2,000	90.00	184.624	75.51	24.4
96	1.18	30.59	7,481	90.09	79,000	22.17	2,000	90.00	85.823	88.62	17.4
97	1.69	0.59	27,889	63.04	101,000	0.49	2,000	90.00	82.588	89.04	11.7
98	1.59	33.75	4171	95.00	100	99.94	-	-	0.866	99.91	23.1
99	2.40	20.00	15,355	69.08			50	99.92	1.148	99.89	17.4
100	0.73	77.19	1781	97.08	-	-	-	-	0.500	99.95	39.9
101A	0.60	87.50	1494	99.70	85	97.97	100	99.88	1.010	94.37	19.8
101B	1.49	68.96	1034	99.79	65	99.98	125	99.85	0.415	99.74	48.2
102A	1.46	76.45	46,433	27.1	30,000	0.00	>14,000	0.00	5.97	98.59	10.0
102B	3.6	41.94	85,791	34.69	30,000	0.00	>14,000	0.00	19.51	95.38	10.0
103	0.28	74.07	-	-	34	99.97	17	99.66	2.13	99.48	9.4
104A	0.90	16.67	967	98.8	30,000	50.41	560	-24.44	1.492	97.37	20.1
104B	0.19	82.41	1110	98.63	330	99.45	91	79.78	0.740	98.68	20.1
105	0.63	41.67	1821	97.75	190	97.96	555	45.05	-	-	-
106	0.73	-43.10	10,651	87.01	11	99.93	<1	>99.99	110.63	39.58	13.7
107A	0.27	60.29	996	98.31	2,300	92.46	1	90.00	0.980	99.67	20.4
107B	0.05	92.65	2714	95.40	1,000	96.72	1	90.00	0.245	99.92	81.6
108	0.05	91.67	33	99.92	380	98.19	-	-	-	-	-
109	0.16	84.62	<10	>99.00	920	94.25	5	99.8	-	-	-
110	0.06	94.74	121	99.85	1700	-96.25	<1	>99.9	-	-	-
111	0.49	56.61	48,150	32.86	1300	95.67	15	99.0	20.39	91.26	10.8
112	0.30	73.45	44,620	37.78	410	98.63	8	99.47	7.34	96.85	21.8
113	0.12	89.38	134,432	-122.93	30,000	0.00	1	99.86	-	>95.00	6.3

Table A-1. Master data table for laboratory-scale rapid rate filtration pilot plant (page 12 of 12).

	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)
114	0.10	91.15	24,797	58.90	880	96.80	<1	>99.99	5.400	95.25	5.5
115	0.27	78.90	28,257	37.94	40	99.68	<1	>99.99	36.585	84.69	4.9
116	0.23	82.03	21,166	53.52	20	99.76	<1	>99.99	7.840	96.72	11.4
117	1.05	15.32	32,907	5.88	2000	77.78	3	99.62	24.427	97.15	9.8
118	0.46	62.90	104,936	-200.14	140	98.44	5	99.37	21.050	97.55	38.0
119	1.3	18.75	7462	89.71	14,000	9.68	4400	5.3	156.540	41.98	16.8
120	1.3	18.75	10,312	85.78	13,000	16.13	5000	-7.53	171.790	36.33	19.5
121	1.31	18.13	12,915	82.19	13,000	16.13	4600	1.08	171.790	36.33	19.5
122	1.35	15.63	13,397	81.15	<1	>99.90	<1	>99.90	85.470	68.32	5.7
123	1.19	25.63	6563	90.95	16,000	-23.08	200	0.00	125.860	48.72	25.2
124	1.23	23.13	7533	89.61	11,000	31.25	200	0.00	68.180	72.22	19.8
125	27.0	9.09	-	-	520	95.84	<1	>99.99	-	-	-
126A	1.20	66.06	-	-	-	-	<1	>99.90	-	-	-
126B	5.30	83.94	-	-	-	-	<1	>99.90	-	-	-
127A	2.00	85.92	-	-	1500	70.00	<1	>94.40	-	-	-
127B	1.38	90.28	-	-	2200	56.00	14	>94.46	-	-	-
128A	8.90	37.32	-	-	9900	20.80	<1	>99.99	-	-	-
128B	9.20	35.21	-	-	1600	87.20	<1	>99.99	-	-	-
129	7.80	45.07	-	-	-	-	<1	>99.90	-	-	-
130	5.60	60.50	-	-			<1	>79.90	-	-	-
131A	2.00	15.49	-	-			<1	>79.90	-	-	
131B	0.23	98.38	-	-	600		<1	>79.90	-	-	
132	0.78	94.51	-	-	510	98.58	<1	>99.90	-	-	-
133	0.32	98.22	-	-	2540	86.54	1	99.99	<20	99.26	6.00
134	1.15	3.36	-	-	17000	-9.68	>1000	<92.22	45.45	93.90	15.20
135	1.86	-56.30	-	-	6800	56.13	>1000	<92.22	>10	>99.90	11.04
136	1.93	-62.18	-	-	8000	48.39	4100	29.91	-	-	-
137	2.20	-84.87	-	-	2600	83.23	10	99.83	-	-	-
138	3.30	- 177.30	-	-	2310	75.56	5	99.79	-	-	-
139	1.76	-47.90	-	-	780	91.75	>1	<99.99	-	-	-
140	1.03	13.45	-	-	18,000	24.05	10	75.00	-	-	-
141	0.26	78.15	-	-	4100	82.70	-	-	-	-	-
142	2.60	- 118.49	-	-	5200	79.03	<1	-	-	-	-
143	1.68	-41.18	-	-	6200	75.00	<1	-	-	-	-
144	1.51	-26.89	-	-	3000	-233.33	<1	-	-	-	-
145	2.90	- 143.70	-	-	6300	-600.00	<1	-	-	-	-
146	0.09	89.89	-	-	3500	62.85	600	97.55	0.602	99.84	33.21
147	0.10	88.76	-	-	26000	-541.98	300	96.00	<8.45	>83.60	5.91
148	0.12	88.68	-	-	1040	97.98	410	96.72	4.55	93.94	5.3
149	0.10	90.57	-	-	900	97.63	19	99.49	-	-	-
150	0.65	-62.50	-	-	17200	-1.47	>1000	<86.67	-	-	-
151	0.33	17.50	-	-	30,000	-76.99	>1000	<86.67	-	-	-
152	0.06	85.00	-	-	3800	77.65	<10	>99.00	-	-	-
153	0.42	-5.00	-	-	30,000	-76.47	1250	-25.00	-	-	-
154	0.19	52.50	-	-	6700	82.60	250	93.15	-	-	-
155	0.09	77.50	-	-	2600	93.25	6	99.84	-	-	-
156	0.52	-30.00	-	-	2500	95.33	113	98.02	-	-	-
157	0.28	30.00	-	-	4800	91.50	80	99.63	-	-	-
158	0.12	70.00	-	-	3800	93.27	60	99.72	-	-	-
159	0.26	35.00	-	-	5600	90.00	>1000	<97.5	-	-	-
160	0.11	75.56	-	-	2300	95.89	200	99.5	-	-	-
161	0.14	83.53	-	-	730	92.02	<1	99.99	-	-	-
162	0.13	84.70	-	-	35	99.73	28	99.86	-	-	-
163	0.62	27.06	-	-	6200	24.69	2233	48.07	0.000	-	-
164	0.13	84.70	-	-	5920	83.87	100	91.30	0.000	-	-
165	0.24	71.76	-	-	730,000	<46.70	10	99.09	0.000	-	-
166	0.06	92.94	-	-	730,000	<41.18	10	99.00	0.000	-	-
167	0.17	80.00	-	-	-	-	-	-	0.000	-	-
168	0.03	96.47	-	-	38000	32.38	-	-	0.000	-	-
169	0.03	96.47	-	-	1290	94.94	-	-	0.000	-	-
170	0.19	85.00	-	-	-	-	-	-	0.000	-	-
171	0.09	89.41	-	-	-	-	0	100.00	0.000	-	-
172	0.39	54.10	-	-	730,000	<22.68	1	99.33	0.000	-	-
173	1.66	27.80	-	-	20900	-14.84	1100	40.54	0.000	-	-
174	0.59	1.00	-	-	12,600	14.29	100	90.00	-	-	-
175	0.30	53.00	-	-	800	85.45	1000	71.18	-	-	-
176	0.24	65.00	-	-	-	-	<1	99.99	-	-	-
177	0.20	74.00	-	-	230	96.17	33	99.50	-	-	-
178	0.16	79.00	-	-	8,120	-98.05	95	98.61	-	-	-

Table A-2. *Giardia* cyst removal efficiency corrected for detection limits (page 1 of 4).

Run No.	Membrane Filter Sampling Efficiency 1/	Detection Limit 2/	Effluent *Giardia* Cyst Conc. Corrected for Recovery Efficiency 3/* (cyst/L)	Removal Efficiency 4/
42	15.3	3.039	3.039	99.39
43	16.33	4.469	4.469	99.06
44	11.57	9.244	9.244	94.15
45	4.65	9.5579	41.55	91.69
46	54.1	1.22	122.29	74.55
47	54.1	3.006	17.94	96.27
48	95.37	0.626	0.626	99.87
49	95.37	0.012	0.012	>99.9
50	23.41	2.141	10.700	97.77
51	79.76	4.179	4.179	99.13
52	108.66	1.227	1.227	99.74
53	77.49	2.53	2.53	99.47
54	68.0	2.45	30.85	93.83
55	80.9	2.747	2.74	99.45
56	34.0	4.45	44.56	91.09
57	34.0	5.767	5.767	98.85
58	45.0	2.339	64.22	87.16
59	-	-	-	-
60	-	-	-	-
61	-	-	-	-
62	-	-	-	-
63	-	-	-	-
64	-	-	-	-
65	-	-	-	-
66	73.75	0.1934	0.1934 4	99.96
67	66.67	1.229	1.229	99.75
68	87.0	0.912	28.8	94.24
69	103.85	4.1866	4.186	99.16
70	103.85	0.5631	3.1	99.38
71	62.8	0.514	0.514	99.95
72	70.0	0.2239	0.224	99.97
73	-	-	-	-
74	41.6	1.5116	5.190	99.48
75	32.4	8.122	40.34	95.97
76	20.0	3.03	55.55	94.45
77	20.0	4.098	-	-
78	20.0	3.9683	-	-
79	20.0	4.52	-	-

Table A-2. Giardia cyst removal efficiency corrected for detection limits (page 2 of 4).

Run No.	Membrane Filter Sampling Efficiency 1/	Detection Limit 2/	Effluent Giardia Cyst Conc. Corrected for Recovery Efficiency 3/* (cyst/L)	Removal Efficiency 4/
80	-	-	-	-
81	-	-	-	-
82	-	-	-	-
83	-	-	-	-
84	55.79	-	-	-
85A	60.0	2.525	2.525	99.95
85B	60.0	1.2626	9.47	99.81
86A	16.0	6.3131	6.3131	99.87
86B	16.0	1.3631	1.3631	99.97
87A	35.6	2.8374	1.37	99.97
87B	35.6	0.5255	0.52	99.99
88A	47.37	2.9733	4.61	99.91
88B	47.37	11.11	11.11	99.78
89A	53.0	2.7952	2.79	99.94
89B	53.0	0.756	4.93	99.90
90A	80.8	1.2134	1.2134	99.98
90B	80.8	0.3536	0.3536	99.99
91A	63.64	1.5405	1.540	99.97
91B	63.64	0.4622	0.4522	99.9
92A	-	-	-	-
92B	-	-	-	-
93A	-	-	-	-
93B	-	-	-	-
94	95.74	1.05	60.8	92.27
95	95.79	0.8557	192.7	75.71
96	95.79	1.1994	89.9	88.62
97	95.79	1.7845	86.2	89.04
98	68.38	1.266	1.26	99.80
99	67.48	1.703	1.70	99.89
100	13.94	3.59	3.59	99.94
101A	22.82	4.426	4.42	99.37
101B	22.82	1.819	1.82	99.74
102A	60.30	3.3002	9.9	98.59
102B	60.30	3.3002	32.35	95.38
103	66.8	3.192	3.192	99.47
104A	9.42	1.056	15.8	97.37
104B	9.42	1.056	7.85	98.70
105	-	-	-	-

Table A-2. *Giardia* cyst removal efficiency corrected for detection limits (page 3 of 4).

Run No.	Membrane Filter Sampling Efficiency[1]	Detection Limit[2]	Effluent Giardia Cyst Conc. Corrected for Recovery Efficiency[3]* (cyst/L)	Removal Efficiency[4]
106	41.61	3.508	265.87	34.57
107A	50.21	1.952	1.952	94.67
107B	50.21	0.488	0.49	99.92
108	-	-	-	-
109	-	-	-	-
110	-	-	-	-
111	97.15	1.906	20.99	91.25
112	97.15	0.945	7.55	96.85
113	48.08	6.63	6.63	97.24
114	48.08	7.59	11.23	95.32
115	119.5	3.416	30.6	84.64
116	119.5	1.459	6.56	96.72
117	85.8	2.3786	28.7	97.15
118	85.8	0.6134	24.50	97.55
119	89.67	1.328	174.57	41.81
120	89.67	1.14	91.5	36.41
121	89.67	1.143	191.26	36.25
122	89.67	3.913	95.3	68.23
123	81.82	0.9767	153.8	48.72
124	81.82	1.2345	83.3	72.22
125	-	-	-	-
126A	-	-	-	-
126B	-	-	-	-
127A	-	-	-	-
127B	-	-	-	-
128A	-	-	-	-
128B	-	-	-	-
129	-	-	-	-
130	-	-	-	-
131A	-	-	-	-
131B	-	-	-	-
132	-	-	-	-

Table A-2. _Giardia_ cyst removal efficiency corrected for detection limits (page 4 of 4).

[1] _Giardia_ cysts were not used during Runs 1-41.

[2] (Influent No. of cyst detected/No. of cyst added 100 = Membrane filter sampling efficiency recovery.

[3] (20 cysts)/[(Membrane filter sampling efficiency recovery)(Effluent volume sampled)]

[4] (No. of cysts detected effluent)/[(Membrane filter sampling recovery) (Effluent volume sampled)]

[5] 100 {1 - (Effluent cysts concentration corrected for detection limit/ Influent cysts concentration added)]

*Detection limit when zero cysts are reported.

Note: Procedures for these calculations are given in Appendix J.

APPENDIX B

MASTER DATA TABLE FOR FIELD-SCALE RAPID RATE FILTRATION PILOT PLANT

Table B-1 contains all experimental data obtained during experiments using the field-scale rapid rate filtration pilot plant, e.g. the Neptune Microfloc Waterboy R . As with Table A-1, each row of the table contains data obtained from a given test run. The table has three parts: i) influent water characteristics, shown in Table B-1(a); ii) chemical basin information, shown in Table B-1(b); and iii) filter conditions and effluent water conditions, shown in Table B-1(c). Table B-1 served as a source from which other tables and graphs were derived related to field-scale testing results. Appendix H and the latter part of Chapter 4 contain these tables and graphs.

Table B-1 is intended to be used either in place, or as a "fold out." The fold out table can be constructed using copies or originals, of Tables B-1(a), B-1(b), and B-1(c), constructed as shown below:

Table B-1(a)	Table B-1(b)	Table B-1(c)
Sheet 1	Sheet 1	Sheet 1
Sheet 2	Sheet 2	Sheet 2
Sheet 3	Sheet 3	Sheet 3

Table B-1(a). Master Data Table (Sheet 1).

Test Identification		Influent Water Characteristics					
Run #	Date	Source of Water	Temp. (°C)	Turbidity (NTU)	Coliforms (#/100ml)	*Giardia* Designed (cyst/liter)	*Giardia* Detected (cyst/liter)
1	11/9/82	HT	10.0	9.0	2/	1/	1/
2	11/14/82	HT	7.5	9.0	2/	1/	1/
3	12/30/82	HT	6.0	9.5	2/	1/	1/
4	12/31/82	HT	6.0	9.5	2/	1/	1/
5	1/2/83	HT	6.0	9.5	2/	1/	1/
5	1/3/83	HT	6.0	9.5	2/	1/	1/
7	1/4/83	HT	6.0	9.6	2/	1/	1/
8	1/5/83	HT	6.0	9.0	2/	1/	1/
9	1/7/83	HT	5.5	9.0	2/	1/	1/
10	1/8/83	HT	5.5	9.0	2/	1/	1/
11	1/8/83	HT	5.5	8.0	2/	1/	1/
12	1/8/83	HT	5.5	8.0	2/	1/	1/
13	1/9/83	HT	5.5	8.5	2/	1/	1/
14	1/9/83	HT	5.5	8.5	2/	1/	1/
15	1/20/83	HT	5.0	9.0	2/	1/	1/
16	1/20/83	HT	5.0	9.0	2/	1/	1/
17	1/2/83	HT	5.0	9.0	2/	1/	1/
18	1/21/83	HT	5.0	9.0	2/	1/	1/
19	1/23/83	HT	5.0	9.5	2/	1/	1/
20	2/2/83	HT	5.0	9.0	2/	1/	1/
21	2/2/83	HT	5.0	9.0	2/	1/	1/
22	2/9/83	HT	5.0	9.0	2/	1/	1/
23	4/23/83	PR	8.0	27.0	2/	1/	1/
24	4/23/83	PR	8.0	27.0	2/	1/	1/
25	4/23/83	PR	8.0	27.0	2/	1/	1/
26	4/23/83	PR	8.0	27.0	2/	1/	1/
27a	4/26/83	PR	9.0	30.0	2/	1/	1/
27b	4/26/83	PR	9.0	30.0	2/	1/	1/
28a	4/26/83	PR	9.0	30.0	2/	1/	1/
28b	4/26/83	PR	9.0	30.0	2/	1/	1/
29	5/25/83	PR	9.0	44.0	2/	1/	1/
30	5/25/83	PR	9.0	44.0	2/	1/	1/
31	5/25/83	PR	9.0	44.0	2/	1/	1/
32	5/25/83	PR	11.0	35.0	2/	1/	1/
33	5/26/83	PR	10.0	32.0	2/	1/	1/
34	5/26/84	PR	10.0	27.0	2/	1/	1/
35	5/29/83	PR	7.5	34.0	2/	1/	1/
36	5/29/83	PR	7.5	35.0	2/	1/	1/
37	5/29/83	PR	7.5	35.0	2/	1/	1/
38	5/31/83	PR	7.0	16.0	2/	1/	1/
39	6/1/83	PR	7.0	17.0	2/	1/	1/
40	6/1/83	PR	8.0	17.0	2/	1/	1/
41	6/1/83	PR	8.0	12.0	2/	1/	1/
42	6/1/83	PR	8.0	12.0	2/	1/	1/
43	7/3/83	HT	10.0	7.0	2/	1/	1/
44	7/3/83	HT	10.0	7.0	2/	1/	1/
45	7/4/83	HT	10.0	7.0	2/	1/	1/
46	7/4/83	HT	10.0	7.0	2/	1/	1/
47	7/4/83	HT	10.0	7.0	2/	1/	1/
48	7/5/83	HT	10.0	7.0	2/	1/	1/
49	7/12/83	HT	10.0	7.0	2/	135	10
50	7/12/83	HT	10.0	7.0	2/	135	130
51	7/13/83	HT	10.0	7.0	300	220	110
52	7/14/83	HT	10.0	7.0	220	220	30

1/ No *Giardia* cysts or coliform bacteria injected
2/ Coliform bacteria were not monitored
3/ Cysts were of questionable viability
4/ No *Giardia* injected, therefore no *Giardia* sampling
5/ No effluent turbidity sample
6/ Alum dosages are in mg/l as $Al_2(SO_4)_3 \cdot 14H_2O$

cut line

Table B-1(a). Master Data Table (Sheet 2).

Test Identification			Influent Water Characteristics				
Run #	Date	Source of Water	Temp. (°C)	Turbidity (NTU)	Coliforms (#/100ml)	*Giardia* Designed (cyst/liter)	*Giardia* Detected (cyst/liter)
53	7/13/83	HT	11.0	7.0	2/	1/	1/
54	7/14/83	HT	10.0	7.0	2/	1/	1/
55	7/14/83	HT	10.0	7.0	2/	1/	1/
56	7/14/83	HT	10.0	7.0	2/	1/	1/
57	7/15/83	HT	10.0	7.0	2/	245	25
58	7/15/83	HT	10.0	7.0	2/	245	45
59	7/18/83	HT	12.0	7.0	1200	210	25
60	7/19/83	HT	12.0	7.0	13,000	150	50
61	7/19/83	HT	12.0	7.0	23,000	150	16
62	7/19/83	HT	12.0	7.0	2/	800	60
63	7/25/83	HT	12.0	7.0	2/	1/	1/
64	7/25/83	HT	12.0	7.0	2/	1/	1/
65	7/25/83	HT	11.0	7.0	2/	1/	1/
66	7/25/83	HT	11.0	7.0	2/	1/	1/
67	8/3/83	HT	12.0	7.0	2/	1/	1/
68	8/3/83	HT	12.0	7.0	2/	1/	1/
69	8/3/83	HT	12.0	7.0	2/	1/	1/
70	8/4/83	HT	12.0	7.0	2/	1/	1/
71	8/11/83	HT	12.0	7.0	2/	1/	1/
72	8/12/83	HT	12.0	7.0	2/	1/	1/
73	8/12/83	HT	11.0	7.0	3600	700	3/
74	8/12/83	HT	11.0	7.0	1500	700	3/
75	8/14/83	HT	13.0	7.0	3600	525	3/
76	8/14/83	HT	13.0	7.0	2700	525	3/
77	8/14/83	HT	13.0	7.0	2/	1/	1/
78	8/15/83	HT	12.0	7.0	2/	1/	1/
79	8/15/83	HT	12.0	7.0	8700	550	35
80	8/16/83	HT	13.0	7.0	2/	1/	1/
81	8/16/83	HT	13.0	7.0	2/	1/	1/
82	8/16/83	HT	13.0	7.0	2/	1/	1/
83	8/16/83	HT	13.0	7.0	2/	1/	1/
84	8/23/83	HT	12.0	7.0	2/	1/	1/
85	8/23/83	HT	12.0	7.0	2/	1/	1/
86	8/23/83	HT	12.0	7.0	2/	1/	1/
87	8/23/83	HT	12.0	7.0	2/	1/	1/
88	8/23/83	HT	12.0	7.0	2/	1/	1/
89	8/23/83	HT	12.0	7.0	2/	1/	1/
90	8/24/83	HT	12.0	7.0	16,000	550	250
91	8/24/83	HT	12.0	7.0	16,000	550	350
92	8/24/83	HT	12.0	7.0	30,000	1000	800
93	8/27/83	HT	12.0	7.0	2/	1/	1/
94	8/28/83	HT	12.0	7.0	2/	1/	1/
95	8/28/83	HT	12.0	7.0	2/	1/	1/
96	8/28/83	HT	12.0	7.0	2/	1/	1/
97	8/28/83	HT	12.0	7.0	2/	1/	1/
98	8/28/83	HT	12.0	7.0	20,000	2400	2000
99	8/28/83	HT	12.0	7.0	15,000	2400	1700
100	8/29/83	HT	12.0	7.0	2/	1/	1/
101	8/30/83	HT	12.0	7.0	2/	1/	1/
102	8/30/83	HT	12.0	7.0	2/	1/	1/
103	8/30/83	HT	12.0	7.0	2/	1/	1/
104	8/31/83	HT	12.0	7.0	2/	1/	1/
105	8/31/83	HT	12.0	7.0	1200	450	200
106	8/31/83	HT	12.0	7.0	2500	1000	75

1/ No *Giardia* cysts or coliform bacteria injected
2/ Coliform bacteria were not monitored
3/ Cysts were of questionable viability
4/ No *Giardia* injected, therefore no *Giardia* sampling
5/ No effluent turbidity sample
6/ Alum dosages are in mg/l as $Al_2(SO_4)_3 \cdot 14H_2O$

Table B-1(a). Master Data Table (Sheet 3).

Test Identification		Influent Water Characteristics					
Run #	Date	Source of Water	Temp. (°C)	Turbidity (NTU)	Coliforms (#/100ml)	*Giardia* Designed (cyst/liter)	*Giardia* Detected (cyst/liter)
107	11/1/83	PR	7.0	.60	2/	1/	1/
108	11/1/83	PR	7.0	.55	2/	1/	1/
109	11/1/83	PR	7.0	.45	2/	1/	1/
110	11/2/83	PR	7.0	.50	2/	1/	1/
111	11/2/83	PR	7.0	.45	2/	1/	1/
112	11/2/83	PR	7.0	.45	2/	1/	1/
113	11/5/83	PR	7.0	.60	2/	1/	1/
114	11/5/83	PR	7.0	.60	2/	1/	1/
115	11/5/83	PR	7.0	.70	2/	1/	1/
116	11/5/83	PR	7.0	.60	2/	1/	1/
117	11/10/83	PR	2.0	.40	15000	1500	260
118	11/15/83	PR	2.0	.65	2/	1/	1/
119	11/15/83	PR	2.0	.65	2/	1/	1/
120	11/15/83	PR	2.0	.65	2/	1/	1/
121	11/15/83	PR	2.0	.65	2/	1/	1/
122	11/17/83	PR	3.0	.65	2/	1/	1/
123	12/3/83	PR	1.0	.60	6900	1400	325
124	12/3/83	PR	1.0	.60	6900	1400	325
125	12/6/83	PR	1.0	.55	9000	1300	1300
126	12/6/83	PR	1.0	.55	9000	1300	1300
127	12/10/83	PR	1.0	.90	2/	400	175
128	12/10/83	PR	1.0	.90	2/	400	175
129	12/15/83	PR	1.0	.60	3500	1/	1/
130	1/4/84	PR	1.0	.80	2/	1/	1/
131	1/4/84	PR	1.0	.80	2/	1/	1/
132	1/4/84	PR	1.0	.80	2/	1/	1/
133	1/4/84	PR	1.0	.80	2/	1/	1/
134	1/6/84	PR	1.0	.70	2/	1/	1/
135	1/6/84	PR	1.0	.70	2/	1/	1/
136	1/6/84	PR	1.0	.70	2/	1/	1/
137	1/8/84	PR	1.0	.70	2/	1/	1/
138	1/8/84	PR	1.0	.70	10000	2600	1300

1/ No *Giardia* cysts or coliform bacteria injected
2/ Coliform bacteria were not monitored
3/ Cysts were of questionable viability
4/ No *Giardia* injected, therefore no *Giardia* sampling
5/ No effluent turbidity sample
6/ Alum dosages are in mg/l as $Al_2(SO_4)_3 \cdot 14H_2O$

Table B-1(b). Master Data Table (Sheet 1).

	Chemical Basin Information					
Run #	Alum Dosage6/ (mg/l)	Polymer Dosage (mg/l)	Type of Polymer	G(sec^{-1})	T(sec)	GT
1	0	1.0	572C	750	202	151,500
2	0	1.0	573C	750	222	166,500
3	0	0.5	573C	714	228	162,700
4	0	0.5	572C	714	212	151,400
5	0	1.5	573C	714	221	157,800
5	0	1.5	572C	714	212	151,400
7	0	4.0	573C	714	204	145,700
8	0	9.0	573C	714	228	163,000
9	0	7.0	8181	702	221	155,100
10	0	4.0	8102	702	217	152,300
11	0	8.0	8102	702	207	145,300
12	0	11.0	8102	702	203	142,500
13	0	1.0	8102	702	205	143,900
14	0	6.5	572C	702	203	142,500
15	0	1.5	572C	691	280	193,500
16	0	4.5	572C	691	256	176,900
17	0	5.5	572C	691	259	178,900
18	0	2.5	572C	691	228	157,500
19	0	2.5	572C	691	242	167,200
20	0	3.0	573C	691	217	150,000
21	0	7.0	573C	691	219	151,300
22	0	2.0	573C	691	223	154,100
23	0	1.5	572C	720	202	145,400
24	0	4.0	572C	720	202	145,400
25	0	8.5	572C	720	202	145,400
26	0	30	572C	720	202	145,400
27a	0	4.0	572C	726	207	150,300
27b	0	9.0	572C	726	207	150,300
28a	0	17.0	572C	726	207	150,300
28b	0	35.0	572C	726	207	150,300
29	0	10.5	572C	726	238	172,800
30	0	8.0	572C	726	238	172,800
31	0	5.0	572C	726	238	172,800
32	0	21.0	572C	767	238	182,500
33	0	6.5	572C	750	217	162,750
34	0	0	none	750	217	162,750
35	0	9.0	572C	774	238	184,200
36	0	0	none	774	240	185,800
37	0	12.5	572C	774	238	184,200
38	0	7.0	572C	782	248	194,000
39	30	0	none	782	269	210,400
40	18	0	none	720	311	223,900
41	12	0	none	720	230	165,600
42	25	0	none	720	238	171,400
43	0	3.0	573C	750	185	137,700
44	0	2.0	573C	750	180	134,700
45	0	1.0	573C	750	175	131,300
46	0	4.5	573C	750	175	131,300
47	0	6.5	573C	750	170	127,500
48	0	2.5	572C	750	180	135,000
49	0	2.5	573C	750	175	131,300
50	0	0	none	750	180	135,000
51	0	8.0	573C	750	180	135,000
52	0	2.5	8102	750	180	135,000

1/ No *Giardia* cysts or coliform bacteria injected
2/ Coliform bacteria were not monitored
3/ Cysts were of questionable viability
4/ No *Giardia* injected, therefore no *Giardia* sampling
5/ No effluent turbidity sample
6/ Alum dosages are in mg/l as $Al_2(SO_4)_3 \cdot 14H_2O$

cut line

Table B-1(b). Master Data Table (Sheet 2).

	Chemical Basin Information					
Run #	Alum Dose6/ (mg/l)	Polymer Dosage (mg/l)	Type of Polymer	$G(sec^{-1})$	T(sec)	GT
53	0	2.0	8102	755	170	128,400
54	0	0.8	8102	750	180	135,000
55	0	5.0	8102	750	170	127,000
56	0	7.5	8102	750	170	127,000
57	0	0	none	750	180	135,000
58	0	5.5	8102	750	180	135,000
59	0	11.0	8102	760	180	136,800
60	0	0	none	760	180	136,000
61	0	0	none	760	180	136,000
62	0	0	none	760	180	136,000
63	0	1.0	572C	760	180	136,000
64	0	2.5	572C	760	180	136,800
65	0	5.5	572C	755	180	135,900
66	0	11.0	572C	755	180	135,900
67	4	0	none	760	180	136,800
68	12	0	none	760	180	136,800
69	18	0	none	760	180	136,800
70	25	0	none	760	180	136,800
71	0	4.0	572C	760	180	136,800
72	0	2.5	572C	760	180	136,800
73	0	2.5	572C	755	180	135,900
74	0	0	none	755	180	135,900
75	0	1.0	572C	765	180	137,700
76	30	0	none	765	180	137,700
77	30	0	none	765	180	137,700
78	0	3.5	8102	760	180	136,800
79	0	3.5	8102	760	180	136,800
80	0	1.0	8102	765	210	160,700
81	0	4.0	8102	765	210	160,700
82	0	6.0	8102	765	210	160,700
83	0	10.0	8102	765	210	160,700
84	0	3.0	8102	760	210	159,600
85	0	5.0	8102	760	210	159,600
86	0	7.0	8102	760	210	159,600
87	0	15.0	8102	760	210	159,600
88	0	0	8102	760	210	159,600
89	0	4.0	8102	760	180	136,800
90	0	4.0	8102	760	180	136,800
91	0	1.0	8102	760	180	136,800
92	18	0	none	760	180	136,800
93	16	0	none	760	180	136,800
94	20	0	none	760	180	136,800
95	30	0	none	760	180	136,800
96	25	0	none	760	180	136,800
97	10	0	none	760	180	136,800
98	20	0	none	760	180	136,800
99	0	0	none	760	180	136,800
100	0	4.0	8102	760	180	136,800
101	0	4.0	8102	760	180	136,800
102	20	2.0	8102	760	180	136,800
103	20	1.0	8102	760	180	136,800
104	20	4.0	8102	760	180	136,800
105	20	4.0	8102	760	180	136,800
106	20	4.0	8102	760	180	136,800

Cut line

1/ No *Giardia* cysts or coliform bacteria injected
2/ Coliform bacteria were not monitored
3/ Cysts were of questionable viability
4/ No *Giardia* injected, therefore no *Giardia* sampling
5/ No effluent turbidity sample
6/ Alum dosages are in mg/l as $Al_2(SO_4)_3 \cdot 14H_2O$

Table B-1(b). Master Data Table (Sheet 3).

	Chemical Basin Information					
Run #	Alum Dosage6/ (mg/l)	Polymer Dosage (mg/l)	Type of Polymer	G(sec^{-1})	T(sec)	GT
107	0	0	none	782	202	158,000
108	0	0.2	8102	782	235	184,000
109	0	0.5	8102	782	235	184,000
110	0	1.0	8102	782	220	172,000
111	0	2.0	8102	782	220	172,000
112	0	0.2	8102	782	220	172,000
113	3.0	0.6	8102	782	252	197,000
114	3.0	0.6	8102	782	252	197,000
115	3.0	0.2	8102	782	252	197,000
116	3.0	0.07	8102	782	252	197,000
117	0	0	none	645	224	144,000
118	3.0	0	none	645	202	130,000
119	0.5	0	none	645	202	130,000
120	1.5	0	none	645	202	130,000
121	5.5	0	none	645	202	130,000
122	1.0	0	none	661	202	133,000
123	0	0.1	8102	630	224	141,000
124	0	0.4	8102	630	224	141,000
125	0.40	0	none	630	235	148,000
126	5.0	0	none	630	235	148,000
127	3.0	0.2	8102	630	202	127,000
128	3.0	0.4	8102	630	202	127,000
129	0	0	none	630	202	127,000
130	0	0.4	572-C	630	202	127,000
131	0	0.8	572-C	630	202	127,000
132	0	2.0	572-C	630	202	127,000
133	1.5	0.7	572-C	630	202	127,000
134	15	2.0	572-C	630	202	127,000
135	4.5	2.0	572-C	630	202	127,000
136	9.0	2.0	572-C	630	202	127,000
137	30	2.0	572-C	630	202	127,000
138	7.0	2.0	572-C	630	202	127,000

cut line

1/ No *Giardia* cysts or coliform bacteria injected
2/ Coliform bacteria were not monitored
3/ Cysts were of questionable viability
4/ No *Giardia* injected, therefore no *Giardia* sampling
5/ No effluent turbidity sample
6/ Alum dosages are in mg/l as $Al_2(SO_4)_3 \cdot 14H_2O$

Table B-1(c). Master Data Table (Sheet 1).

	Filter Conditions				Effluent Water Conditions		
Run #	Type of Filtration	Length of Run (hr)	Flow Rate (gpm/ft^2)	Turbidity (NTU)	*Giardia* (cyst/liter)	Water Sampled (l)	Coliforms (#/100ml)
1	in-line	9.0	5.0	0.8	1/	4/	2/
2	in-line	8.3	4.6	0.3	1/	4/	2/
3	in-line	6.0	4.4	1.2	1/	4/	2/
4	in-line	5.0	4.8	1.9	1/	4/	2/
5	in-line	4.0	4.6	0.2	1/	4/	2/
5	in-line	4.0	4.8	0.2	1/	4/	2/
7	in-line	5.0	5.0	0.15	1/	4/	2/
8	in-line	2.5	4.4	3.0	1/	4/	2/
9	in-line	2.5	4.6	3.5	1/	4/	2/
10	in-line	3.0	4.7	0.1	1/	4/	2/
11	in-line	4.0	4.9	0.15	1/	4/	2/
12	in-line	3.0	5.0	0.5	1/	4/	2/
13	in-line	3.0	4.9	0.3	1/	4/	2/
14	in-line	3.0	5.0	0.4	1/	4/	2/
15	in-line	1.5	3.6	0.4	1/	4/	2/
16	in-line	1.5	4.0	0.3	1/	4/	2/
17	in-line	1.1	3.9	0.4	1/	4/	2/
18	in-line	2.0	4.4	0.45	1/	4/	2/
19	in-line	2.5	4.2	0.30	1/	4/	2/
20	in-line	1.0	4.7	0.45	1/	4/	2/
21	in-line	0.75	4.6	2.0	1/	4/	2/
22	in-line	5.0	4.1	0.2	1/	4/	2/
23	in-line	0.75	5.0	1.5	1/	4/	2/
24	in-line	0.75	5.0	8.5	1/	4/	2/
25	in-line	0.75	5.0	1.0	1/	4/	2/
26	in-line	0.75	5.0	3.0	1/	4/	2/
27a	in-line	0.80	4.9	3.0	1/	4/	2/
27b	in-line	0.80	4.9	1.5	1/	4/	2/
28a	in-line	0.80	4.9	1.5	1/	4/	2/
28b	in-line	0.80	4.9	6.5	1/	4/	2/
29	in-line	0.80	4.3	2.0	1/	4/	2/
30	in-line	0.80	4.3	1.5	1/	4/	2/
31	in-line	0.80	4.3	2.5	1/	4/	2/
32	in-line	0.80	4.3	3.0	1/	4/	2/
33	in-line	1.0	4.7	1.0	1/	4/	2/
34	in-line	1.0	4.7	10.0	1/	4/	2/
35	in-line	1.0	4.3	1.50	1/	4/	2/
36	in-line	1.0	4.2	1.0	1/	4/	2/
37	in-line	1.2	4.3	1.3	1/	4/	2/
38	in-line	2.8	4.1	1.1	1/	4/	2/
39	in-line	1.0	3.8	4.0	1/	4/	2/
40	in-line	0.8	3.3	12.5	1/	4/	2/
41	in-line	0.7	4.4	10.5	1/	4/	2/
42	in-line	0.5	4.3	10.0	1/	4/	2/
43	in-line	3.0	5.5	0.3	1/	4/	2/
44	in-line	1.0	5.6	0.5	1/	4/	2/
45	in-line	1.0	5.8	1.0	1/	4/	2/
46	in-line	1.0	5.7	0.8	1/	4/	2/
47	in-line	1.0	5.8	2.0	1/	4/	2/
48	in-line	6.0	5.6	0.2	1/	4/	2/
49	in-line	2.0	5.7	0.5	zero	150	2/
50	in-line	1.3	5.6	5/	zero	110	2/
51	in-line	1.3	5.6	5/	zero	110	<1
52	in-line	1.4	5.6	5/	zero	110	10

cut line

1/ No *Giardia* cysts or coliform bacteria injected
2/ Coliform bacteria were not monitored
3/ Cysts were of questionable viability
4/ No *Giardia* injected, therefore no *Giardia* sampling
5/ No effluent turbidity sample
6/ Alum dosages are in mg/l as $Al_2(SO_4)_3 \cdot 14H_2O$

Table B-1(c). Master Data Table (Sheet 2).

	Filter Conditions			Effluent Water Conditions			
Run #	Type of Filtration	Length of Run (hr)	Flow Rate (gpm/ft^2)	Turbidity (NTU)	*Giardia* (cyst/liter)	Water Sampled (l)	Coliforms (#/100ml)
53	in-line	1.0	5.8	0.6	1/	4/	2/
54	in-line	1.0	5.6	1.5	1/	4/	2/
55	in-line	1.0	5.9	0.45	1/	4/	2/
56	in-line	1.0	6.0	0.55	1/	4/	2/
57	in-line	1.4	5.6	6.0	30	150	2/
58	in-line	1.4	5.6	0.4	zero	190	2/
59	in-line	1.4	5.6	1.0	zero	150	20
60	in-line	1.4	5.6	6.0	8	150	>1000
61	in-line	1.4	5.6	6.2	16	150	>1000
62	in-line	1.4	5.6	6.1	235	150	1/
63	in-line	1.0	5.6	0.7	1/	4/	2/
64	in-line	1.0	5.6	0.55	1/	4/	2/
65	in-line	1.0	5.6	0.6	1/	4/	2/
66	in-line	1.0	5.6	2.3	1/	4/	2/
67	in-line	1.0	5.6	6.3	1/	4/	2/
68	in-line	1.0	5.6	2.3	1/	4/	2/
69	in-line	1.0	5.6	1.3	1/	4/	2/
70	in-line	1.0	5.6	1.6	1/	4/	2/
71	in-line	10.5	5.6	0.5	1/	4/	2/
72	in-line	1.0	5.6	0.6	1/	4/	2/
73	in-line	2.0	5.6	0.5	3/	3/	100
74	in-line	2.0	5.6	6.4	3/	3/	1000
75	in-line	2.0	5.6	1.7	3/	3/	680
76	in-line	4.0	5.6	0.2	3/	3/	100
77	in-line	1.0	5.6	1.8	1/	4/	2/
78	in-line	14.0	5.6	0.15	1/	4/	2/
79	in-line	1.5	5.6	0.15	zero	150	50
80	in-line	1.0	4.8	1.4	1/	4/	2/
81	in-line	1.0	4.8	0.4	1/	4/	2/
82	in-line	1.0	4.8	0.5	1/	4/	2/
83	in-line	1.0	4.8	0.6	1/	4/	2/
84	in-line	1.0	4.8	0.4	1/	4/	2/
85	in-line	1.0	4.8	0.4	-	4/	2/
86	in-line	1.0	4.8	1/	4/	2/	
87	in-line	3.0	4.8	0.8	1/	4/	2/
88	in-line	1.0	4.8	5.8	1/	4/	2/
89	in-line	2.0	5.6	0.3	1/	4/	2/
90	in-line	1.8	5.6	0.4	zero	150	70
91	in-line	1.8	5.6	1.2	zero	150	580
92	in-line	1.8	5.6	1.7	25	150	570
93	in-line	1.0	5.6	1.3	1/	4/	2/
94	in-line	1.0	5.6	1.3	1/	4/	2/
95	in-line	1.0	5.6	2.1	1/	4/	2/
96	in-line	1.0	5.6	1.8	1/	4/	2/
97	in-line	1.0	5.6	8.4	1/	4/	2/
98	in-line	1.8	5.6	1.1	125	150	330
99	in-line	1.8	5.6	6.8	1000	150	11,000
100	in-line	1.0	5.6	0.5	1/	4/	2/
101	in-line	1.0	5.6	0.4	1/	4/	2/
102	in-line	1.0	5.6	0.65	1/	4/	2/
103	in-line	1.0	5.6	1.1	1/	4/	2/
104	in-line	1.0	5.6	0.75	1/	4/	2/
105	in-line	1.8	5.6	0.8	zero	150	30
106	in-line	1.8	5.6	0.7	5	150	100

1/ No *Giardia* cysts or coliform bacteria injected
2/ Coliform bacteria were not monitored
3/ Cysts were of questionable viability
4/ No *Giardia* injected, therefore no *Giardia* sampling
5/ No effluent turbidity sample
6/ Alum dosages are in mg/l as $Al_2(SO_4)_3 \cdot 14H_2O$

cut line

Table B-1(c). Master Data Table (Sheet 3).

	Filter Conditions			Effluent Water Conditions			
Run #	Type of Filtration	Length of Run (hr)	Flow Rate (gpm/ft^2)	Turbidity (NTU)	*Giardia* (cyst/liter)	Water Sampled (l)	Coliforms (#/100ml)
107	in-line	1.0	5.0	0.45	1/	4/	2/
108	in-line	1.0	4.3	0.40	1/	4/	2/
109	in-line	1.0	4.3	0.50	1/	4/	2/
110	in-line	1.0	4.6	0.45	1/	4/	2/
111	in-line	1.2	4.6	0.65	1/	4/	2/
112	in-line	1.0	4.6	0.35	1/	4/	2/
113	in-line	0.7	4.0	0.75	1/	4/	2/
114	in-line	1.0	4.0	0.75	1/	4/	2/
115	in-line	1.0	4.0	0.70	1/	4/	2/
116	in-line	1.0	4.0	0.60	1/	4/	2/
117	in-line	1.0	4.5	0.60	180	22	12000
118	in-line	1.0	5.0	0.60	1/	4/	2/
119	in-line	1.0	5.0	0.55	1/	4/	2/
120	in-line	1.0	5.0	0.55	1/	4/	2/
121	in-line	1.0	5.0	0.60	1/	4/	2/
122	in-line	1.0	5.0	0.60	1/	4/	2/
123	in-line	1.8	4.5	1.1	180	22	5700
124	in-line	1.8	4.5	0.85	100	22	3500
125	in-line	1.8	4.3	1.0	850	22	8500
126	in-line	1.8	4.3	1.0	950	22	6500
127	in-line	1.8	5.0	1.1	100	22	2/
128	in-line	1.8	5.0	0.90	125	22	2/
129	in-line	1.0	5.0	0.70	1/	4/	3000
130	in-line	1.0	5.0	0.65	1/	4/	2/
131	in-line	1.0	5.0	0.60	1/	4/	2/
132	in-line	1.0	5.0	0.80	1/	4/	2/
133	in-line	1.0	5.0	0.50	1/	4/	2/
134	in-line	1.0	5.0	1.0	1/	4/	2/
135	in-line	1.0	5.0	0.35	1/	4/	2/
136	in-line	1.0	5.0	0.35	1/	4/	2/
137	in-line	1.0	5.0	3.0	1/	4/	2/
138	in-line	1.8	5.0	0.40	70	22	150

1/ No *Giardia* cysts or coliform bacteria injected
2/ Coliform bacteria were not monitored
3/ Cysts were of questionable viability
4/ No *Giardia* injected, therefore no *Giardia* sampling
5/ No effluent turbidity sample
6/ Alum dosages are in mg/l as $Al_2(SO_4)_3 \cdot 14H_2O$

cut line

APPENDIX C

DESIGN OF LABORATORY-SCALE RAPID RATE FILTRATION PILOT PLANT

Figure C-1 is a schematic drawing of the laboratory-scale rapid rate filtration pilot plant showing each of the components comprising it, rapid mix basin, flocculation basin, sedimentation basin and filtration. The design computation for each components are shown in the paragraph following.

1. Rapid Mix Basin Design

A. Design Condition

1. Temperature of water = 4°C

2. Flow rate = 660 mL/min

B. Criteria

1. Detention time $10 < T < 186$ sec, (Riddick, T. M., 1961)

2. Velocity gradient x time = $3000 < GT < 180{,}000$ (ASCE-AWWA, 1969)

C. Design Procedure

1. Use three basins; first one for lime, second for alum, and third for coagulant aid

2. Detention time 3.1 min = 186 sec

3. Volume of the basin:

$$660 \text{ mL/min} \times 3.1 \text{ min} = 2048.0 \text{ cm}^3$$

$$= 12.7 \text{ cm} \times 12.7 \text{ cm} \times 12.7 \text{ cm}$$

4. Find dimension of tank and impeller, use shape factors

Figure B-2 (Hendricks, 1976) (see Figure C-2)

$\frac{H}{D_t} = 1$ Therefore $H = D_t = 12.7$ cm

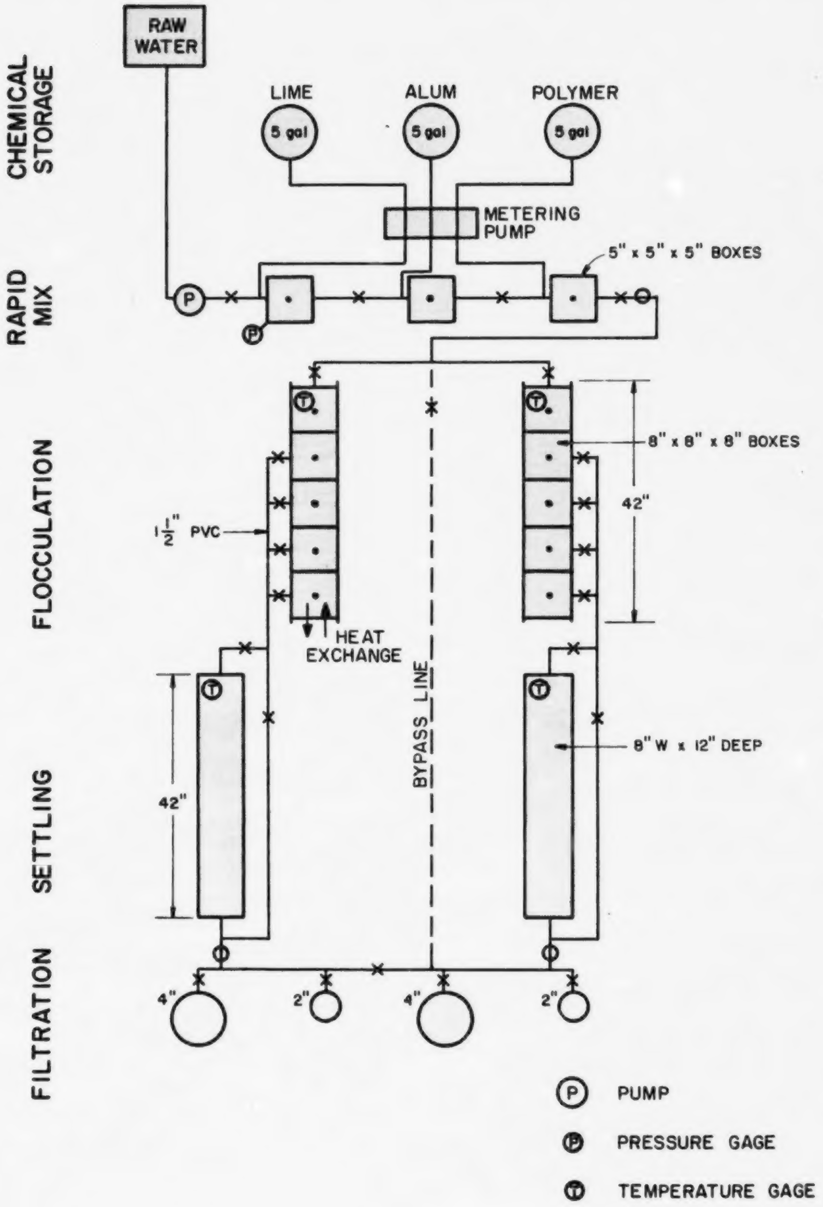

RAW WATER
CHEMICAL STORAGE
LIME
5 gal
ALUM
5 gal
POLYMER
5 gal
METERING PUMP
RAPID MIX
5" x 5" x 5" BOXES
P
P
FLOCCULATION
T
T
8" x 8" x 8" BOXES
42"
1½" PVC
HEAT EXCHANGE
BYPASS LINE
SETTLING
T
T
8" W x 12" DEEP
42"
FILTRATION
4"
2"
4"
2"
P PUMP
P PRESSURE GAGE
T TEMPERATURE GAGE

Figure C-1. Schematic drawing of laboratory-scale rapid rate filtration pilot plant.

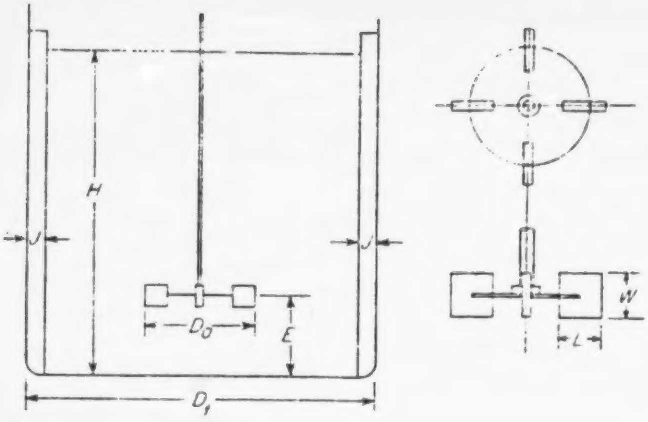


Figure C-2. Measurements of a turbine mixer in a baffle tank (Hendricks, 1976).

$\frac{D_t}{D_a} = 3 \qquad \frac{12.7}{D_a} = 3 \qquad$ Therefore $D_a = 4.233$ cm

$\frac{E}{D_a} = 1 \qquad \frac{E}{4.233} = 1 \qquad$ Therefore $E = 4.233$ cm

$\frac{L}{D_a} = 0.25 \qquad \frac{L}{4.233} = 0.25$

$L = 1.0583$ cm

$\frac{W}{D_a} = 0.25 \qquad \frac{W}{4.233} = 0.25 \qquad W = 1.0583$ cm

$\frac{J}{D_t} = 0.1 \qquad \frac{J}{12.7} = 0.1 \qquad J = 1.27$ cm

5. Let speed of shaft = 150 rpm = 2.5 rps

$$W = \frac{239C_D(1 - k)^3\ S_s^3}{V} \overset{n}{\Sigma} A_i \cdot r_{bi}^3 \cdots 15.17$$

(Hendricks, 1976)

W = total power dissipated by the volume of basin lb-sec^{-1} -ft^{-2}

C_D = drag coefficient = 1.16 (H. E. Rouse, page 249)

k = relative speed of water past blade in rps = 0.24

S_s = speed of shaft in rps

V = volume of basin = 0.0723 ft^3

A = projected area of blade = 0.0017 ft^2

r_{bi} = distance to center of blade from shaft = 0.75" = 0.0625 ft

$$W = \frac{239 \times 1.16(1 - 0.24)^3\ (2.5)^3}{0.0723}$$

$$(0.0017 \times (0.0625)^3 4) = 0.0436 lb - sec^{-1} - ft^2$$

6. $G = \sqrt{\frac{W}{\mu}}$ μ = dynamic viscosity of fluid at 4°C

= 3.273 x 10^{-5} lb - sec - ft^{-2}

$$G = \sqrt{\frac{0.0453}{3.275 \times 10^{-5}}} = 37.7028$$

7. Therefore GT = 37.2028 x 3.1 x 60 = 6919.7283 > 3000. See Figure C-3 for design detail.

2. Flocculation Basin Design

A. Design Condition

1. Temperature of water = 4°C

2. Flow rate = 660 mL/min

B. Criteria (Hendricks, 1976, page 15-36)

1. Detention time D'T = 30 - 60 minutes

2. Number of compartment = 3 - 5

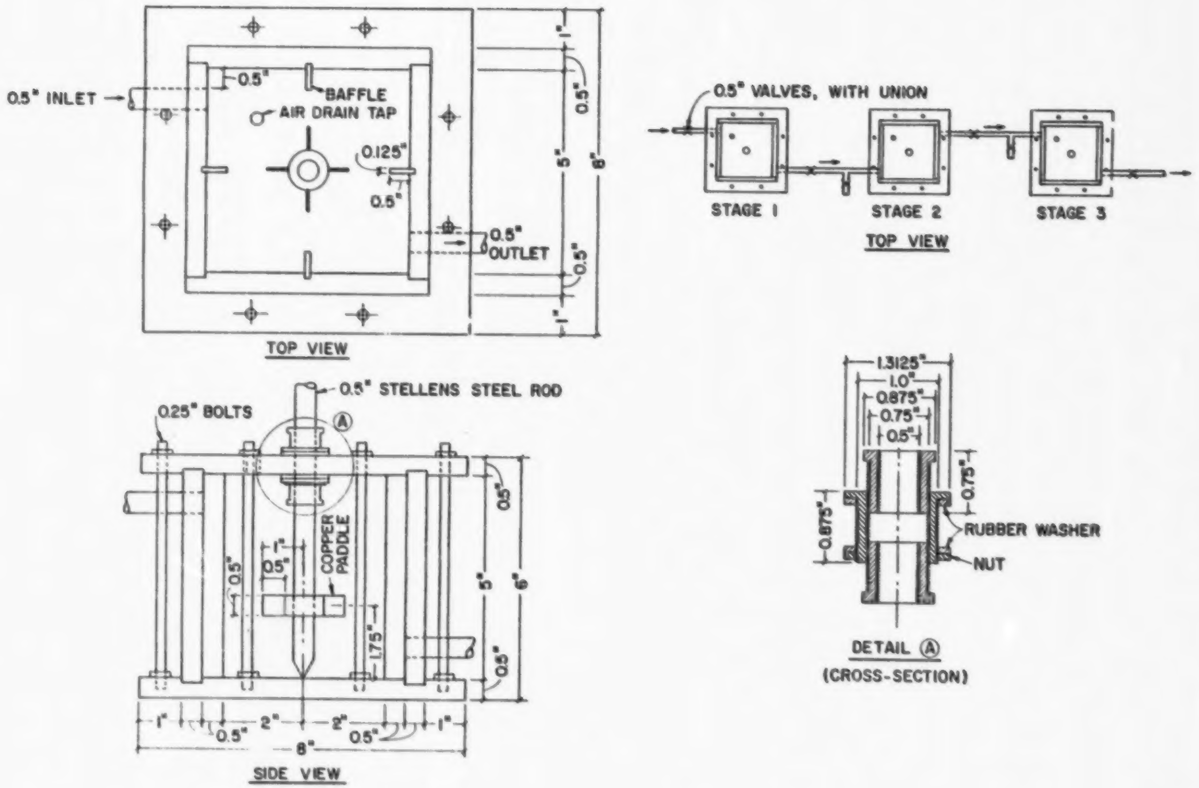

0.5" INLET
0.5"
BAFFLE
AIR DRAIN TAP
0.125"
0.5"
0.5" OUTLET
1"
0.5"
5"
8"
0.5"
1"
TOP VIEW
0.5" VALVES, WITH UNION
STAGE 1
STAGE 2
STAGE 3
TOP VIEW
0.25" BOLTS
0.5" STELLENS STEEL ROD
Ⓐ
COPPER PADDLE
1"
0.5"
0.5"
1.75"
0.5"
5"
6"
0.5"
1"
0.5"
2"
2"
0.5"
1"
8"
SIDE VIEW
1.3125"
1.0"
0.875"
0.75"
0.5"
0.75"
0.875"
RUBBER WASHER
NUT
DETAIL Ⓐ
(CROSS-SECTION)

Figure C-3. Detailed design of rapid mix basin.

3. Velocity gradient $G = 20\ \mathrm{sec}^{-1} - 74\ \mathrm{sec}^{-1}$

4. Velocity gradient x D'T = 23000 - 210,000

5. Area of paddles = (10 - 25)% of the cross-sectional area of basin

6. Speed of paddles = 0.3 - 3.0 ft/sec

C. Design Procedure

1. Let detention time for each compartment = 12.7 min

2. The volume of each compartment = 12.7 min x 660 ml/min

   = 8390 cm sup 3

   = 20.32 cm x 20.32 cm x 20.32 cm

3. Use five compartment

4. Total detention time = 12.7124 x 5 = 63.5620 min

5. Total volume = 8390.1768 x 5 = 41950.92 cm^3

6. Area of paddle

   3/8" x 5 3/4" x 4 = 8.625 $\mathrm{in.}^2$ = 55.6451 cm^2

   (55.6451/20.32 x 20.32) 100 = 13.48%

7. $$W = \frac{239C_D(1-k)^3S_s^3}{V}\sum^{n} A_i\, r_{b2}^3 \cdots$$

   ((15-17) Hendricks, 1978)

   W = total power dissipated by the volume of compartment or conduit

   $\mathrm{lb} - \mathrm{sec}^{-1} - \mathrm{ft}^{-2}$

   C_D = drag coefficient = 1.39 (H. E. Rouse, page 249)

   k = relative speed of water past blade in rps = 0.24

   S_s = speed of shaft in rps

V = volume of basin = 8" x 8" x 8"/12 x 12 x 12

= 0.2963 ft sup 3

A = projected area of blade =

5 3/4" x 3/8"/12 x 12 = 0.015 ft^2

r_b = distance to center of blade for a shaft

$= \frac{2}{12}$ ft, $\frac{1}{12}$ ft

$$W = \frac{239 \times 1.39(1 - 0.24)^3 \times S_s^3}{0.2936}$$

$$(0.015 \times (\frac{2}{12})^3 \times 2 + 0.015 \times (\frac{1}{12})^3 \times 2)$$

$$W = 0.0768S_s^3$$

8. $G = \sqrt{\frac{W}{\mu}}$

μ = dynamic viscosity of fluid at 4°C

3.273×10^{-5} lb - sec - ft^{-2}

9. $$G = \sqrt{\frac{0.0768(S_s)^3}{3.273 \times 10^{-5}}} = 48.431(S_s)^{3/2}$$

10. Let S_s = 40, 30, 20 rmp or 0.667, 0.5, 0.333 rps

11. $G_1 \cdot T$ = 26.4 x 762 = 20116

$G_2 \cdot T$ = 17.1 x 762 = 13030

$G_3 \cdot T$ = 9.3 x 762 = 7,086

ΣGT = 40,232

12. ΣGT = 40,232

Use three compartment volume of each one is 8390.1768 cm^3 with area of paddle = 8.625 $in.^2$, speed of shaft at 40, 30, and 20 rpm for each one. See Figure C-4, Detail Design of Flocculation Basin.

3. Sedimentation Tank Design

A. Design Condition

1. Temperature of water = 4^oC

2. Flow rate = 1321.358 mL/min = 22.0226 mL/sec

B. Design Criteria

1. Surface flow rate = 20 - 33 m/day

(500 - 800 gpd/ft^2) (E. W. Steel and T. McGhee, page 234)

C. Design Procedure

1. $q = \mu_t \times A$ (Linvil G. Rich, page 87)

q = volumetric rate of clarification cm^3/sec

μ_t = settling velocity cm/sec

A = cross section area of rectangular volume in plan perpendicular to the direction of subsidence cm^2

$22.0226\ cm^3/sec = 0.023158\ cm/sec\ (20\ m/day) \times A$

$A = 950.9730\ cm^2$

2. Choose 20.32 cm width and 46.8 cm length or 8 inch width and 18.4 inch length

3. Size of particle will settle

$$V = \frac{1}{18}\frac{1}{\mu}(\gamma_{floc} - \gamma_w)\ d^2$$

Stokes law (12-15) (Hendricks, 1976)

V = settling velocity L/T = 0.023158 cm/sec

μ = dynamic viscosity FT/L^2 = 1.567 centpoise at 4^oC

γ_{floc} = specific weight of floc F/L^3 = 1.18 (Table 12-12, Hendricks, 1976)

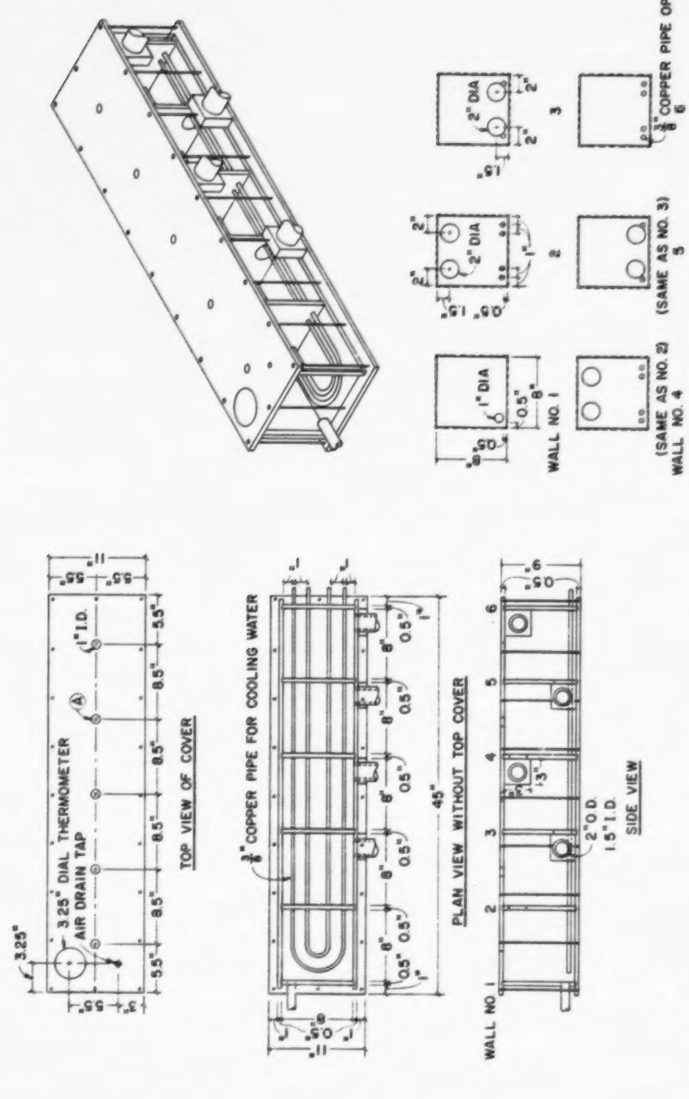

3.25" DIAL THERMOMETER
AIR DRAIN TAP
1" I.D.
TOP VIEW OF COVER
1/8" COPPER PIPE FOR COOLING WATER
45"
PLAN VIEW WITHOUT TOP COVER
2" O.D.
1.5" I.D.
SIDE VIEW
WALL NO. 1
1" DIA
2" DIA
(SAME AS NO. 2)
WALL NO. 4
(SAME AS NO. 3)
5
3/8" COPPER PIPE OPENING
6
NOTE: DASHED LINES INDICATE ADDITIONAL DIMENSION OF 0.125"
(ON ALL FOUR SIDES)

Figure C-4. Detailed design of flocculation basin.

γ_w = specific weight of water $F/L^3 = 1$ at 4°C

d = diameter of floc L

$$0.023158 = \frac{100 \times 981}{18 \times 1.567} (1.18 - 1)d^2$$

d = 0.0037 cm = 36.99 µm or greater; size of floc will settle

See Figure C-5 for Detail Design of Sedimentation Tanks.

4. Filter Design

A. Design Condition

1. Temperature of water = 4°C
2. Flow rate = 660 mL/min

B. Design Criteria (Table 16-5, Hendricks, 1976)

1. Filtration rate = single media = 2 - 5 gpm/ft^2

   dual media = 3 - 6 gpm/ft^2

2. Media: singl or dual
3. Depth of media

   Single sand = 24 - 30 "

   Dual sand and anthracite = 12", 18 - 30"

4. Effective size

   Single: Sand = 0.35 - 50 mm

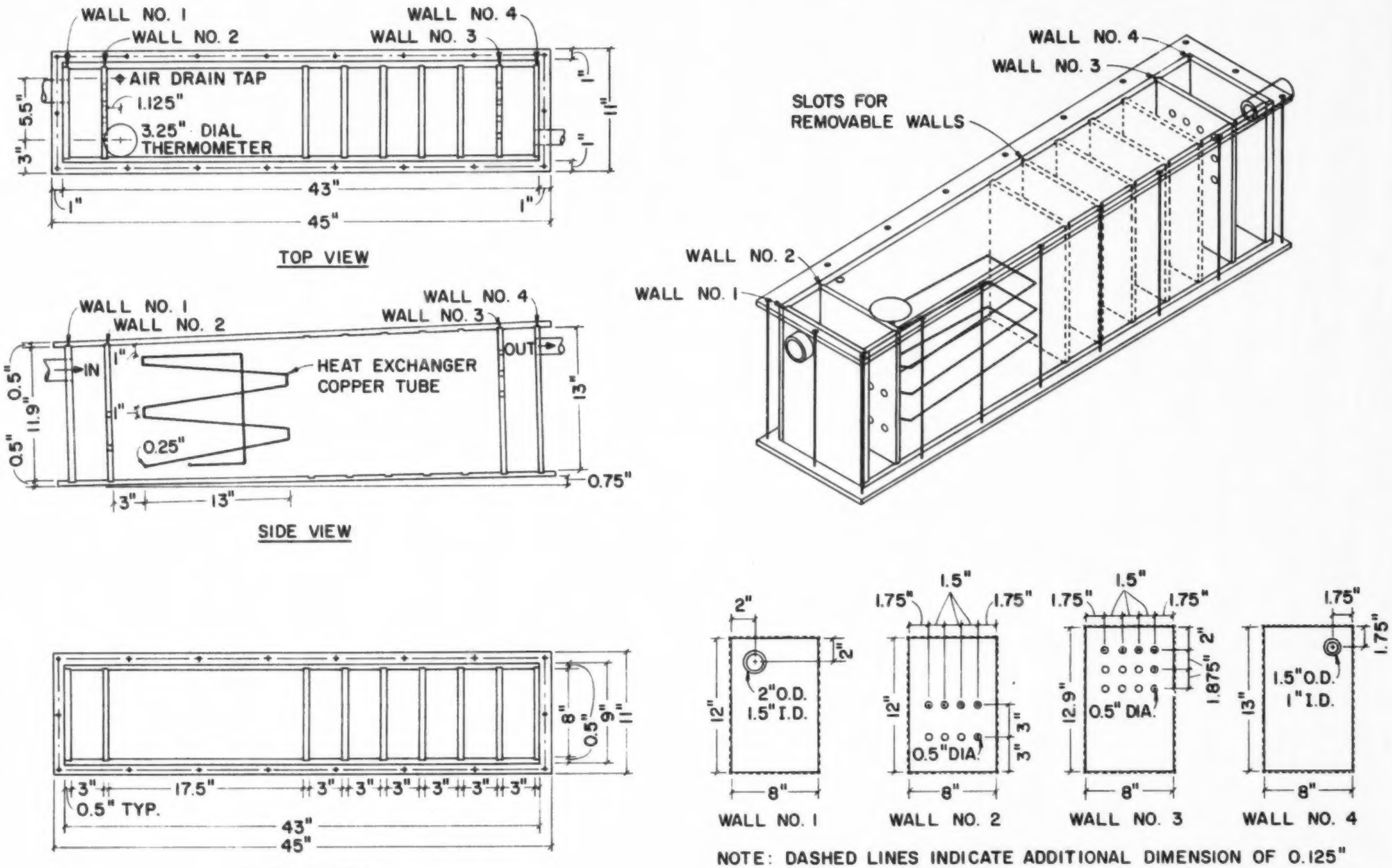
   Dual: Sand = 0.4 - 0.5, anthracite = 0.8 - 1.4

5. Uniformity coefficient

   Single: Sand 1.3 - 1.7

   Dual: Sand 1.3 - 1.7, anthracite = 1.7

6. Under system; porous plates or gravel support-pipe underdrain
7. Backwash rate 10 - 20 gpm/ft^2
8. Backwash period 5 - 10 min


WALL NO. 1
WALL NO. 2
WALL NO. 4
WALL NO. 3
AIR DRAIN TAP
1.125"
3.25" DIAL THERMOMETER
5.5"
3"
1"
11"
43"
45"
TOP VIEW
WALL NO. 1
WALL NO. 2
WALL NO. 4
WALL NO. 3
IN
OUT
HEAT EXCHANGER COPPER TUBE
1"
0.25"
0.5"
11.9"
13"
0.75"
3"
13"
SIDE VIEW
3"
17.5"
0.5" TYP.
8"
0.5"
9"
11"
43"
45"
BOTTOM VIEW
WALL NO. 4
WALL NO. 3
SLOTS FOR REMOVABLE WALLS
WALL NO. 2
WALL NO. 1
2"
2" O.D.
1.5" I.D.
12"
8"
WALL NO. 1
1.75"
1.5"
3"
0.5" DIA.
WALL NO. 2
12.9"
1.875"
WALL NO. 3
1.5" O.D.
1" I.D.
13"
WALL NO. 4

NOTE: DASHED LINES INDICATE ADDITIONAL DIMENSION OF 0.125"
(ON ALL FOUR SIDES)

Figure C-5. Detailed design of sedimentation basin.

C. Design Procedure

1. Area of filter = A

   $Q = v \times A$

   Q = flow rate = 660 mL/min

   v = filtration rate = 2 gpm/ft^2 = 8.2584 cm/min

   A = area of filter

   660 cm^3/min = 8.2584 cm/min x A

   Therefore A = 80.058 cm^2

   Therefore Diameter of filter = 5 cm = 2 inches

2. Media: Single: Sand

3. Depth of media = 30" sand

4. Effective size = 0.45 mm

5. Uniformity coefficient = 1-5

6. Constant flow filtration = 660 mL/min

7. Underdrain system = porous plate (see Figure C-6 for detail)

8. Backwash rate = 15 gpm/ft^2 with air

9. Period of backwash = 10 min
   See Figure C-6 for filter design detail.

5. Design of Flow Basin

A. Design Condition

1. Temperature of water = 4°C

2. Flow rate = 660 mL/min

B. Design Criteria

1. Convenient velocity of flow carrying flocs without breakup flocs

C. Design Procedure

1. Let the size of pipe = 1 1/2" = 3.81 cm

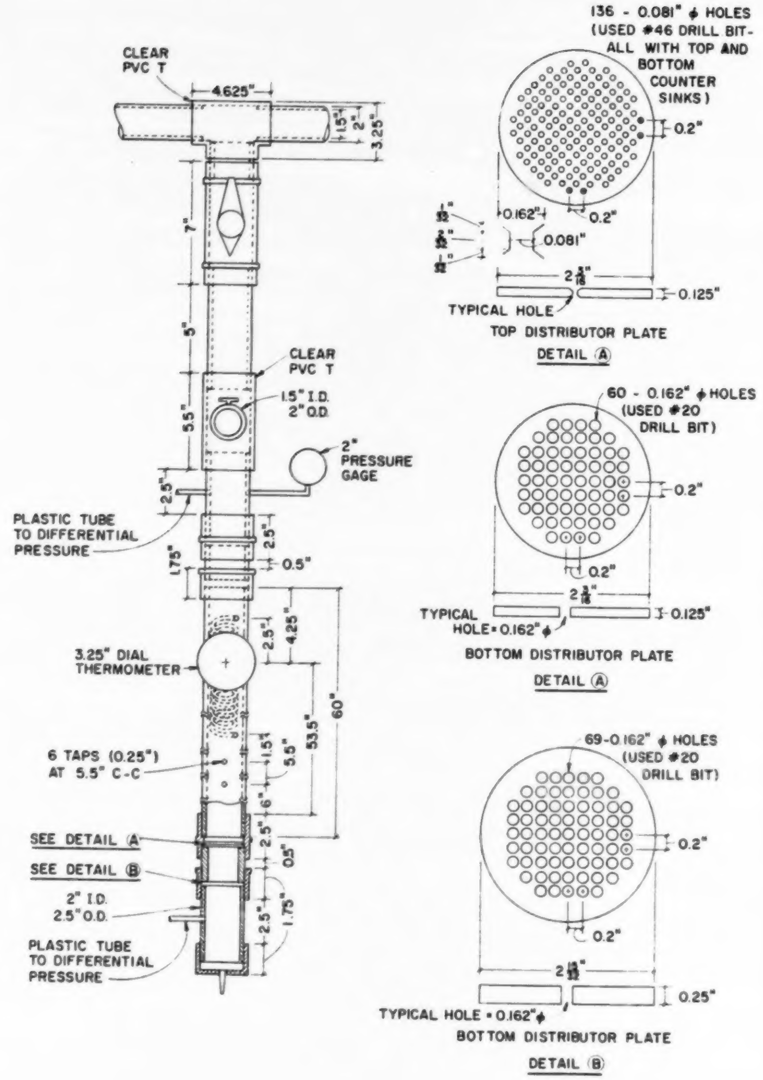

CLEAR PVC T
4.625"
1.5"
2"
3.25"
7"
5"
CLEAR PVC T
5.5"
1.5" I.D. 2" O.D.
2" PRESSURE GAGE
2.5"
PLASTIC TUBE TO DIFFERENTIAL PRESSURE
2.5"
1.75"
0.5"
4.25"
2.5"
3.25" DIAL THERMOMETER
60"
53.5"
6 TAPS (0.25") AT 5.5" C-C
1.5"
5.5"
6"
SEE DETAIL (A)
2.5"
SEE DETAIL (B)
0.5"
2" I.D. 2.5" O.D.
2.5"
1.75"
PLASTIC TUBE TO DIFFERENTIAL PRESSURE
136 - 0.081" ϕ HOLES (USED #46 DRILL BIT- ALL WITH TOP AND BOTTOM COUNTER SINKS)
0.2"
0.162"
0.2"
1/32"
2/32"
1/32"
0.081"
2 3/16"
0.125"
TYPICAL HOLE
TOP DISTRIBUTOR PLATE
DETAIL (A)
60 - 0.162" ϕ HOLES (USED #20 DRILL BIT)
0.2"
0.2"
2 3/16"
0.125"
TYPICAL HOLE = 0.162" ϕ
BOTTOM DISTRIBUTOR PLATE
DETAIL (A)
69-0.162" ϕ HOLES (USED #20 DRILL BIT)
0.2"
0.2"
2 13/32"
0.25"
TYPICAL HOLE = 0.162" ϕ
BOTTOM DISTRIBUTOR PLATE
DETAIL (B)

Figure C-6. Filter design detail.

2. Velocity of flow

$Q = A \times v$

Q = flow rate = 660 cm^3/min

A = area of pipe = $(3.81)^2 \times 1/4 \times 3.1416$

= 11.40 cm^2

v = velocity of flow = cm/min

$660 = 11.4 \times v$

Therefore v = 57.8901 cm/min = 0.9648 cm/sec

3. If the maximum size of flocs = 100 μm

$$v = \frac{1}{18\mu} (\gamma_{floc} - \gamma_w)\, d^2$$

Stocks law (12-15) Hendricks

$$= \frac{100 \times 981}{18 \times 1.567} (1.18 - 1)(100 \times 10^{-6} \times 100)^2$$

v = 0.0626 cm/sec = 3.7562 cm/min

Therefore v of flow/v of floc = $\frac{57.8901}{3.7562}$ = 15.41 so the flow will carry the flocs

4. R Reynolds number

$R = \frac{vD}{v} < 2{,}000$ (H. Rouse, page 174)

$$\frac{vLp}{\mu} = \frac{0.9648 \times 3.81 \times 100}{1.567}$$

$= 234.5897 < 2{,}000$

Therefore the flow is stable.

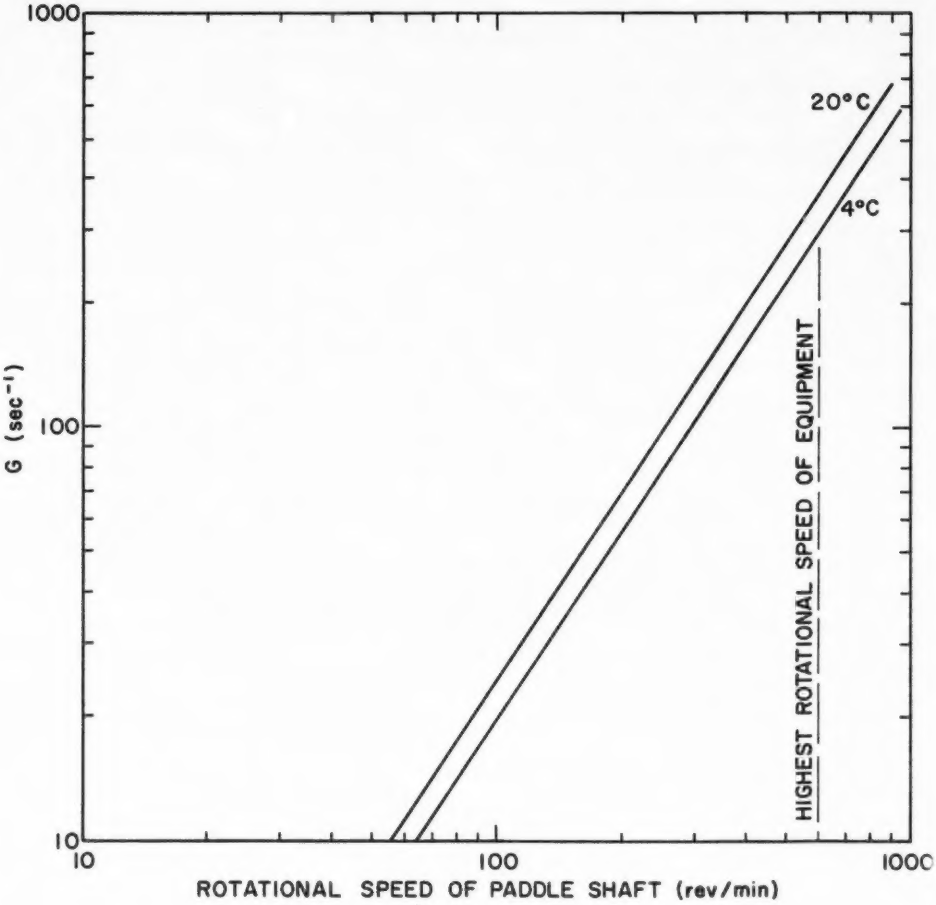


Figure C-7. Velocity gradient (G sec^{-1} versus revolution per minute of paddle shaft for coagulation box. Laboratory scale rapid rate filtration pilot plant. Volume of box is 2048 cm^3. Paddle design shown in Figure C-3.

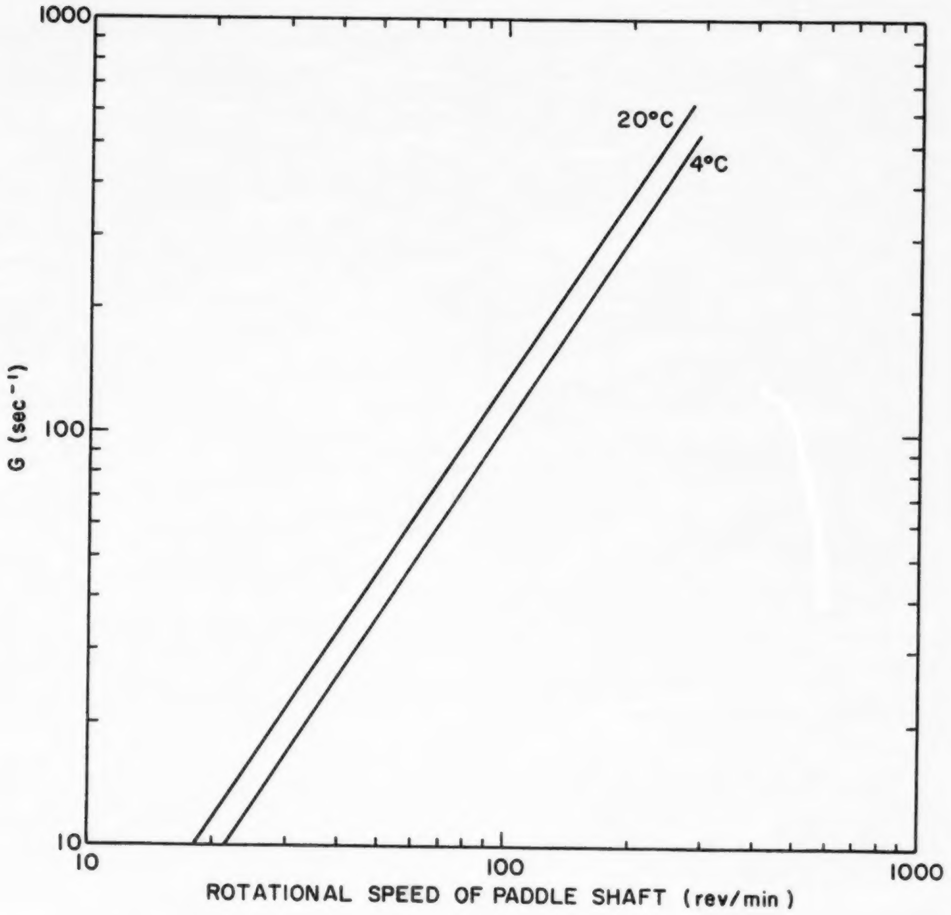


Figure C-8. Velocity gradient (G sec^{-1} versus revolution per minute (rpm) for flocculation compartment. Laboratory-scale rapid rate filtration pilot plant. Volume of compartment is 8390 cm^3.

APPENDIX D

DESCRIPTION OF THE FIELD-SCALE RAPID RATE FILTRATION PILOT PLANT AND ITS OPERATION

DESCRIPTION

The field-scale rapid rate filtration pilot plant used in this research was a Neptune Microfloc Model WB-27 WATER BOY® package water treatment plant. Its nominal capacity is 76 L/min (20 gpm) and it is capable of satisfying the water needs of a community of 190 people. The plant was purchased by the Drinking Water Research Division of the U.S. Environmental Protection Agency in Cincinnati, who designed a 22 foot trailer to hold the WATER BOY as shown in Figure D-1; thus it became a mobile water treatment plant.

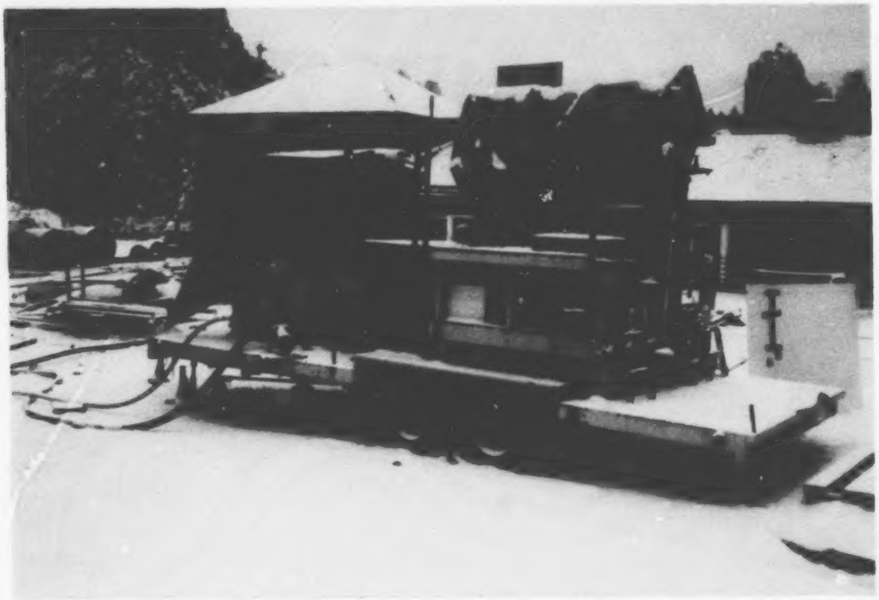
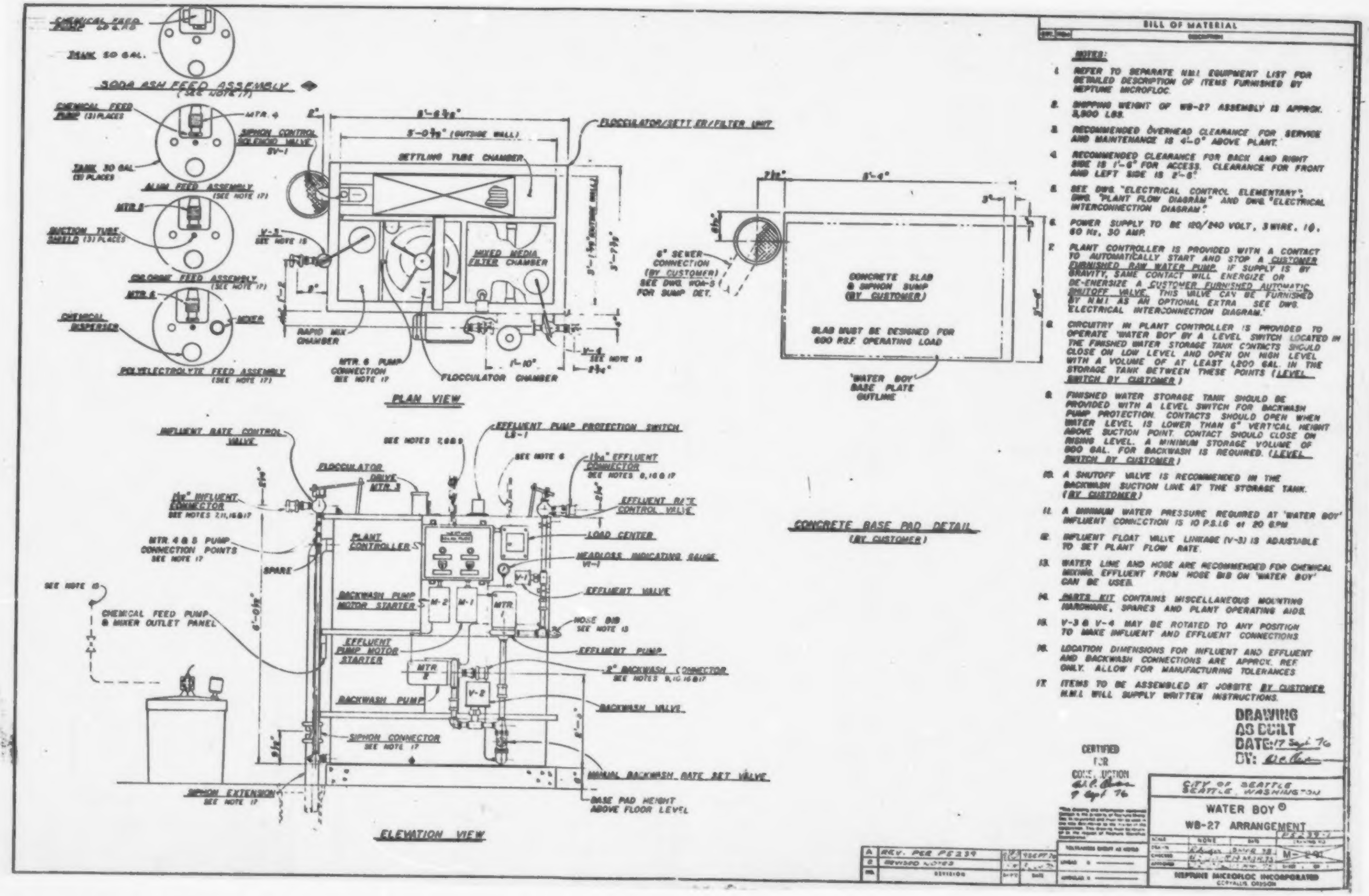


Figure D-1. The Neptune Microfloc WATER BOY® field-scale rapid rate filtration pilot plant as set up at the Fort Collins Water Treatment Plant No. 1 for low-turbidity testing. Water was obtained from the Cache La Poudre River.

Figure D-2 is a drawing of the Neptune Microfloc WATER BOY® showing elevation and plan views. Figure D-3 is a flow diagram for the WATER BOY®,


CHEMICAL FEED PUMP
TANK 50 GAL.
SODA ASH FEED ASSEMBLY ◆
(SEE NOTE 17)
CHEMICAL FEED PUMP (3) PLACES
MTR. 4
SIPHON CONTROL SOLENOID VALVE SV-1
TANK 30 GAL. (3) PLACES
ALUM FEED ASSEMBLY (SEE NOTE 17)
MTR. 5
SUCTION TUBE SHIELD (3) PLACES
CHLORINE FEED ASSEMBLY (SEE NOTE 17)
MTR. 6
CHEMICAL DISPERSER
MIXER
POLYELECTROLYTE FEED ASSEMBLY (SEE NOTE 17)
8'-6 3/8"
5'-0 3/8" (OUTSIDE WALL)
FLOCCULATOR/SETTLER/FILTER UNIT
SETTLING TUBE CHAMBER
V-3 SEE NOTE 15
MIXED MEDIA FILTER CHAMBER
RAPID MIX CHAMBER
MTR. 6 PUMP CONNECTION SEE NOTE 17
FLOCCULATOR CHAMBER
1'-10"
V-4 SEE NOTE 15
PLAN VIEW
6" SEWER CONNECTION (BY CUSTOMER) SEE DWG. WOA-5 FOR SUMP DET.
CONCRETE SLAB & SIPHON SUMP (BY CUSTOMER)
SLAB MUST BE DESIGNED FOR 600 PSF OPERATING LOAD
'WATER BOY' BASE PLATE OUTLINE
CONCRETE BASE PAD DETAIL (BY CUSTOMER)
INFLUENT RATE CONTROL VALVE
SEE NOTES 7,8 & 9
EFFLUENT PUMP PROTECTION SWITCH LS-1
SEE NOTE 6
1 1/2" EFFLUENT CONNECTOR SEE NOTES 8,16 & 17
FLOCCULATOR DRIVE MTR. 3
1 1/2" INFLUENT CONNECTOR SEE NOTES 7,11,16 & 17
EFFLUENT RATE CONTROL VALVE
PLANT CONTROLLER
LOAD CENTER
MTR. 4 & 5 PUMP CONNECTION POINTS SEE NOTE 17
HEADLOSS INDICATING GAUGE VI-1
SPARE
SEE NOTE 13
CHEMICAL FEED PUMP & MIXER OUTLET PANEL
BACKWASH PUMP MOTOR STARTER
M-2
M-1
MTR 1
V-1
EFFLUENT VALVE
HOSE BIB SEE NOTE 13
EFFLUENT PUMP MOTOR STARTER
EFFLUENT PUMP
MTR 2
2" BACKWASH CONNECTOR SEE NOTES 9,10,16 & 17
V-2
BACKWASH PUMP
BACKWASH VALVE
SIPHON CONNECTOR SEE NOTE 17
MANUAL BACKWASH RATE SET VALVE
SIPHON EXTENSION SEE NOTE 17
BASE PAD HEIGHT ABOVE FLOOR LEVEL
ELEVATION VIEW
BILL OF MATERIAL
DRAWING AS BUILT
DATE: 17 Sept 76
CERTIFIED FOR CONSTRUCTION
9 Sept 76
A REV. PER PE239
B REVISED NOTES
CITY OF SEATTLE SEATTLE, WASHINGTON
WATER BOY ®
WB-27 ARRANGEMENT
NEPTUNE MICROFLOC INCORPORATED
CORVALLIS, OREGON

NOTES:

1. REFER TO SEPARATE NMI EQUIPMENT LIST FOR DETAILED DESCRIPTION OF ITEMS FURNISHED BY NEPTUNE MICROFLOC.
2. SHIPPING WEIGHT OF WB-27 ASSEMBLY IS APPROX. 3,900 LBS.
3. RECOMMENDED OVERHEAD CLEARANCE FOR SERVICE AND MAINTENANCE IS 4'-0" ABOVE PLANT.
4. RECOMMENDED CLEARANCE FOR BACK AND RIGHT SIDE IS 1'-6" FOR ACCESS. CLEARANCE FOR FRONT AND LEFT SIDE IS 2'-6".
5. SEE DWG. "ELECTRICAL CONTROL ELEMENTARY", DWG. "PLANT FLOW DIAGRAM" AND DWG. "ELECTRICAL INTERCONNECTION DIAGRAM".
6. POWER SUPPLY TO BE 120/240 VOLT, 3 WIRE, 1Ø, 60 Hz, 30 AMP.
7. PLANT CONTROLLER IS PROVIDED WITH A CONTACT TO AUTOMATICALLY START AND STOP A CUSTOMER FURNISHED RAW WATER PUMP. IF SUPPLY IS BY GRAVITY, SAME CONTACT WILL ENERGIZE OR DE-ENERGIZE A CUSTOMER FURNISHED AUTOMATIC SHUTOFF VALVE. THIS VALVE CAN BE FURNISHED BY NMI AS AN OPTIONAL EXTRA. SEE DWG. 'ELECTRICAL INTERCONNECTION DIAGRAM.'
8. CIRCUITRY IN PLANT CONTROLLER IS PROVIDED TO OPERATE 'WATER BOY' BY A LEVEL SWITCH LOCATED IN THE FINISHED WATER STORAGE TANK. CONTACTS SHOULD CLOSE ON LOW LEVEL AND OPEN ON HIGH LEVEL WITH A VOLUME OF AT LEAST 1,200 GAL. IN THE STORAGE TANK BETWEEN THESE POINTS (LEVEL SWITCH BY CUSTOMER)
9. FINISHED WATER STORAGE TANK SHOULD BE PROVIDED WITH A LEVEL SWITCH FOR BACKWASH PUMP PROTECTION. CONTACTS SHOULD OPEN WHEN WATER LEVEL IS LOWER THAN 6" VERTICAL HEIGHT ABOVE SUCTION POINT. CONTACT SHOULD CLOSE ON RISING LEVEL. A MINIMUM STORAGE VOLUME OF 800 GAL. FOR BACKWASH IS REQUIRED. (LEVEL SWITCH BY CUSTOMER)
10. A SHUTOFF VALVE IS RECOMMENDED IN THE BACKWASH SUCTION LINE AT THE STORAGE TANK. (BY CUSTOMER)
11. A MINIMUM WATER PRESSURE REQUIRED AT 'WATER BOY' INFLUENT CONNECTION IS 10 P.S.I.G. at 20 GPM
12. INFLUENT FLOAT VALVE LINKAGE (V-3) IS ADJUSTABLE TO SET PLANT FLOW RATE.
13. WATER LINE AND HOSE ARE RECOMMENDED FOR CHEMICAL MIXING. EFFLUENT FROM HOSE BIB ON 'WATER BOY' CAN BE USED.
14. PARTS KIT CONTAINS MISCELLANEOUS MOUNTING HARDWARE, SPARES AND PLANT OPERATING AIDS.
15. V-3 & V-4 MAY BE ROTATED TO ANY POSITION TO MAKE INFLUENT AND EFFLUENT CONNECTIONS.
16. LOCATION DIMENSIONS FOR INFLUENT AND EFFLUENT AND BACKWASH CONNECTIONS ARE APPROX. REF. ONLY. ALLOW FOR MANUFACTURING TOLERANCES.
17. ITEMS TO BE ASSEMBLED AT JOBSITE BY CUSTOMER. NMI WILL SUPPLY WRITTEN INSTRUCTIONS.

Figure D-2. Neptune Microfloc diagram of the WATER BOY ® showing elevation and plan views.

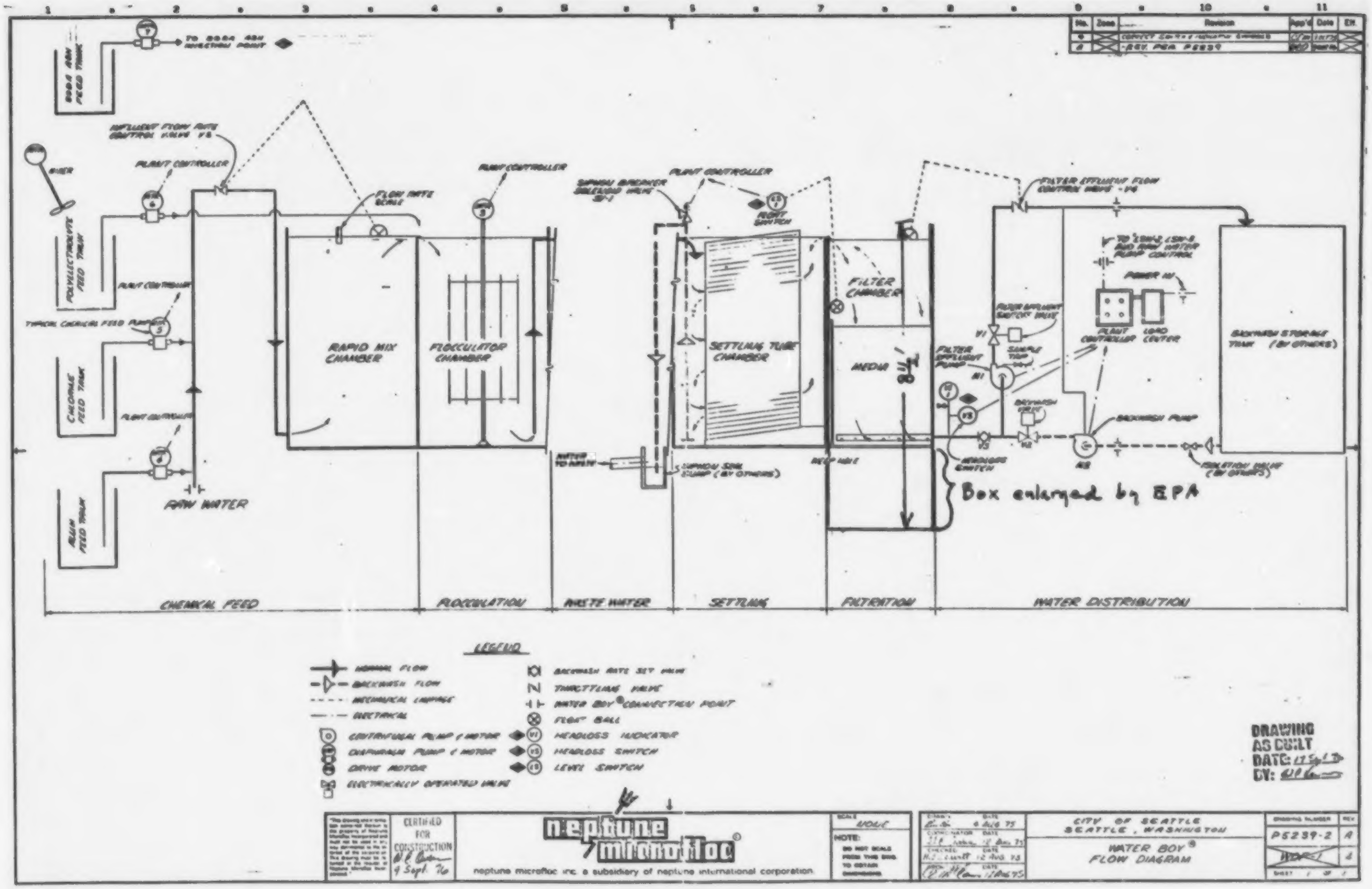

SODA ASH FEED TANK
TO SODA ASH INJECTION POINT
MIXER
POLYELECTROLYTE FEED TANK
INFLUENT FLOW RATE CONTROL VALVE V5
PLANT CONTROLLER
TYPICAL CHEMICAL FEED PUMP
CHLORINE FEED TANK
ALUM FEED TANK
RAW WATER
FLOW RATE SCALE
RAPID MIX CHAMBER
FLOCCULATOR CHAMBER
SIPHON BREAKER SOLENOID VALVE SV-1
FLOAT SWITCH
SETTLING TUBE CHAMBER
WATER TO WASTE
SIPHON SEAL SUMP (BY OTHERS)
FILTER CHAMBER
MEDIA
8 1/2'
FILTER EFFLUENT FLOW CONTROL VALVE - V4
FILTER EFFLUENT SHUTOFF VALVE
SAMPLE TAP
FILTER EFFLUENT PUMP
HEADLOSS SWITCH
BACKWASH PUMP
TO LSH-2, LSH-3 AND RAW WATER PUMP CONTROL
POWER IN
PLANT CONTROLLER
LOAD CENTER
BACKWASH STORAGE TANK (BY OTHERS)
ISOLATION VALVE (BY OTHERS)
Box enlarged by EPA
CHEMICAL FEED
FLOCCULATION
WASTE WATER
SETTLING
FILTRATION
WATER DISTRIBUTION
LEGEND
NORMAL FLOW
BACKWASH FLOW
MECHANICAL LINKAGE
ELECTRICAL
CENTRIFUGAL PUMP & MOTOR
DIAPHRAGM PUMP & MOTOR
DRIVE MOTOR
ELECTRICALLY OPERATED VALVE
BACKWASH RATE SET VALVE
THROTTLING VALVE
WATER BOY® CONNECTION POINT
FLOAT BALL
HEADLOSS INDICATOR
HEADLOSS SWITCH
LEVEL SWITCH
No. Zone Revision App'd Date Ch.
REV. PER P5239
DRAWING AS BUILT
CERTIFIED FOR CONSTRUCTION
4 Sept 76
neptune microfloc
neptune microfloc inc. a subsidiary of neptune international corporation
SCALE NONE
NOTE: DO NOT SCALE FROM THIS DWG. TO OBTAIN DIMENSIONS
CITY OF SEATTLE
SEATTLE, WASHINGTON
WATER BOY®
FLOW DIAGRAM
P5239-2
A

Figure D-3. Neptune Microfloc flow diagram of the WATER BOY ® showing processes and hydraulics.

supplied by Neptune Microfloc Inc., illustrating process hydraulics. As shown in Figures D-2 and D-3, the WATER BOY ® is a complete rapid rate filtration water treatment plant consisting of: rapid mix basin, flocculation basin with variable speed paddle wheel, sedimentation consisting of tube settlers at 7.5 degrees, and filtration box.

When the WATER BOY ® arrived at Colorado State University, in August 1982, after work at Oneida, New York conducted by Clarkson College of Technology, it contained the filtration media shown in Figure D-4. This media was used in experiments here during initial familiarization testing, but was replaced in March 1983 by media obtained locally. Figure D-5 shows the filtration media used after March 1983 and which has remained in the pilot plant filter bed for all subsequent testing.

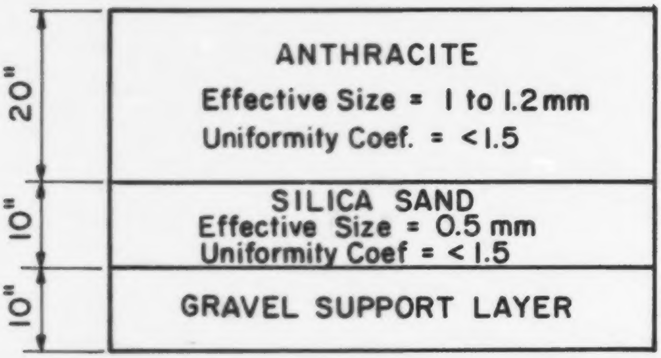

20"
ANTHRACITE
Effective Size = 1 to 1.2mm
Uniformity Coef. = <1.5
10"
SILICA SAND
Effective Size = 0.5 mm
Uniformity Coef = < 1.5
10"
GRAVEL SUPPORT LAYER

Figure D-4. Filtration media used during familiarization testing. Media used was packed by Clarkson College of Technology, Postdam, New York.

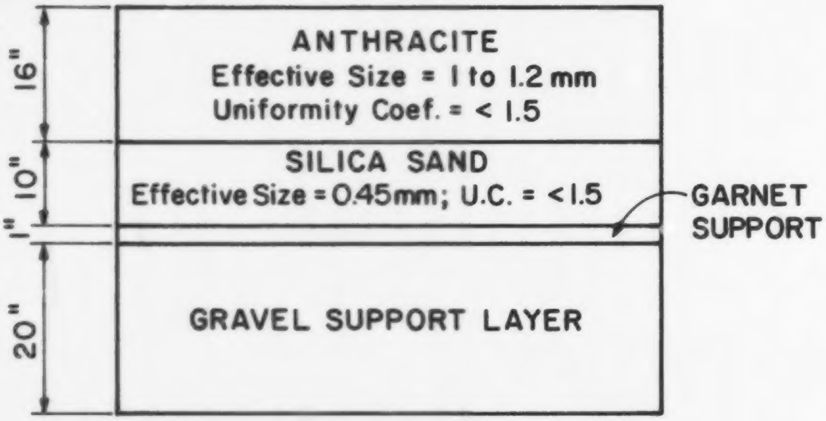
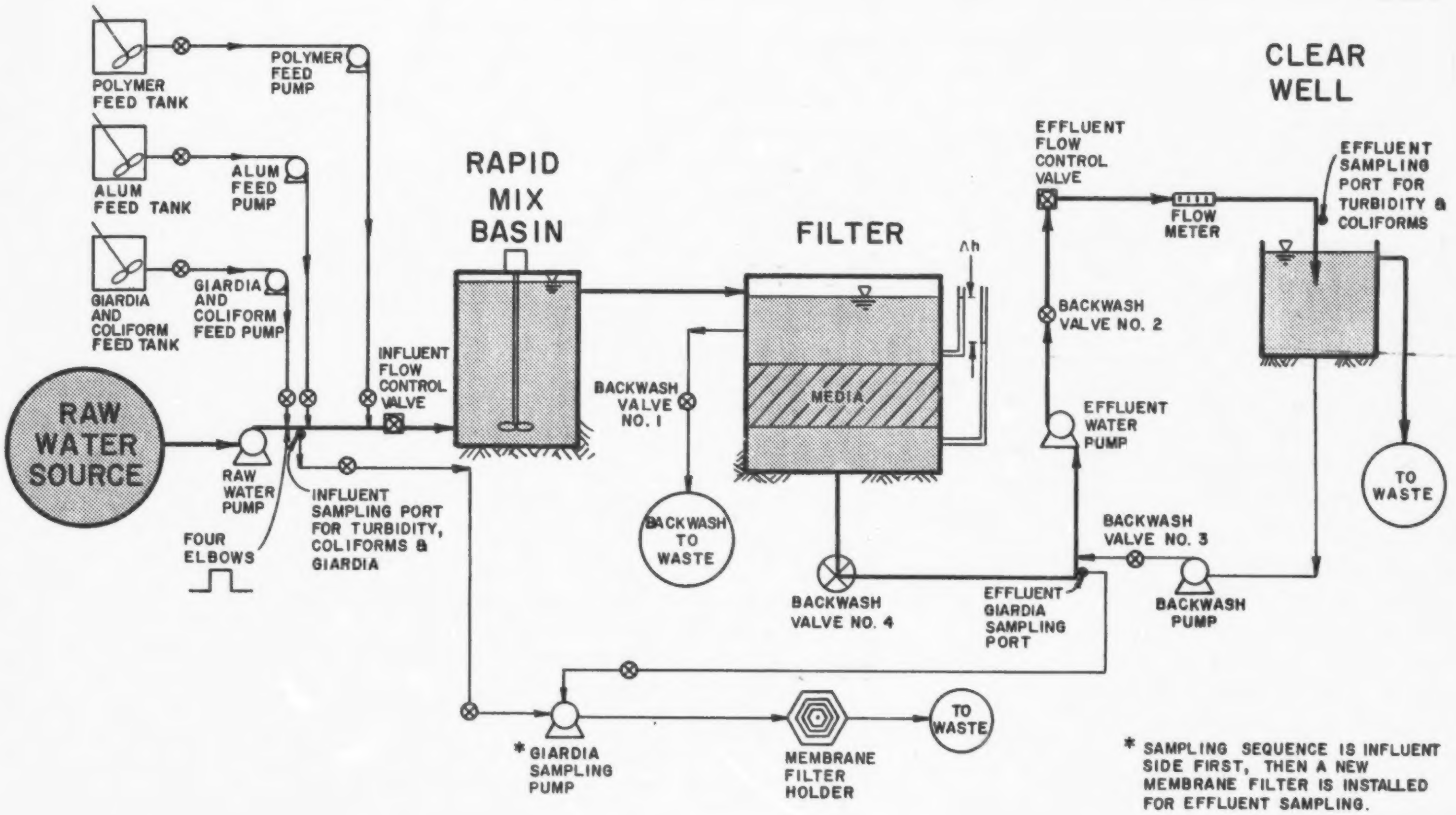

16"
ANTHRACITE
Effective Size = 1 to 1.2 mm
Uniformity Coef. = < 1.5
10"
SILICA SAND
Effective Size = 0.45mm; U.C. = < 1.5
1"
GARNET SUPPORT
20"
GRAVEL SUPPORT LAYER

Figure D-5. Filtration media used during Spring Runoff, Horsetooth, and Low-Turbidity testing. Anthracite was obtained from the Fort Collins Water Treatment Plant No. 1, and the sand was obtained from the Fort Collins Treatment Plant No. 2.

Table D-1. Appurtenances for operation of field scale rapid rate filtration pilot plant.

Item	Purpose & Specifications	Manufactor	Model #
Raw Water Pump	Pumps Raw Water into Rapid Mix	Goulds Pumps, Inc.	XSH 15
Contaminant Feed Pump	Meters the contaminant batch into the main flow (0 to 1120 mL/min)	Fluid Metering, Inc	RP-D
Alum Feed Pump	Meters alum solution into main flow (0 to 75 mL/min)	Precision Control	111311-361
Polymer Feed Pump	Meters polymer solution into main flow (0 to 75 mL/min)	Precision Control	111311-361
Sodium Thiosulfate Feed Pump	Feeds $Na_2S_2O_3$ solution into effluent stream for dechlorination (50 to 1000 cc/min)	Cole Parmer	212
Giardia Sampling Pump	Diverts sampling stream from main flow through membrane filter (0 to 8.5 L/min)	Grainger	Rotary Beam Pump 1P771
Giardia Sampling Pump Motor	Drives *Giardia* sampling pump (3/4 hp)	Grainger	27846
Contaminant Batch Mixer	Agitates contaminant batch	Lightnin Mixers	Series 20
Alum Batch Mixer	Mixes alum solution	Wilkens-Anderson Co.	Power Stirrer
Polymer Batch Mixer	Mixes polymer solution	Cole Parmer	4555 H
Rapid Mix Basin Mixer	Disperses chemicals in rapid mix basin (1/4 hp) 1725 rpm	Lightnin Mixers	Mark II
Membrane Filter Holder	Holds 5 µm pore size 293 mm diameter membrane filters made by Nucleopore Corporation	Gelman Sciences	11873
Ratio Turbidimeter	Measures grab samples for turbidity	Hach Chemical Co.	18900-10
Flow-through Turbidimeter	Monitor influent and effluent turbidity	Hach Chemical Co.	1720-A

[1] Neptune Microfloc Model WB-27 WATER BOY ® package water treatment plant, trailer mounted by EPA.


POLYMER FEED TANK
POLYMER FEED PUMP
ALUM FEED TANK
ALUM FEED PUMP
GIARDIA AND COLIFORM FEED TANK
GIARDIA AND COLIFORM FEED PUMP
RAW WATER SOURCE
RAW WATER PUMP
FOUR ELBOWS
INFLUENT SAMPLING PORT FOR TURBIDITY, COLIFORMS & GIARDIA
INFLUENT FLOW CONTROL VALVE
RAPID MIX BASIN
BACKWASH VALVE NO. 1
BACKWASH TO WASTE
FILTER
MEDIA
Δh
BACKWASH VALVE NO. 4
EFFLUENT GIARDIA SAMPLING PORT
EFFLUENT WATER PUMP
BACKWASH VALVE NO. 2
EFFLUENT FLOW CONTROL VALVE
FLOW METER
CLEAR WELL
EFFLUENT SAMPLING PORT FOR TURBIDITY & COLIFORMS
TO WASTE
BACKWASH VALVE NO. 3
BACKWASH PUMP
* GIARDIA SAMPLING PUMP
MEMBRANE FILTER HOLDER
TO WASTE

* SAMPLING SEQUENCE IS INFLUENT SIDE FIRST, THEN A NEW MEMBRANE FILTER IS INSTALLED FOR EFFLUENT SAMPLING.

Figure D-6. Schematic diagram of the WATER BOY pilot plant showing chemical feed, contaminant feed, and sampling systems

Table D-1 lists the appurtenances which were used with the WATER BOY ® pilot plant. All appurtances except the flow-through turbidimeters were assembled for the purposes of the present research.

Figure D-6 is a flow schematic of the WATER BOY as set up and used in this research. It shows the chemical feed system, contaminant injection system, and contaminant sampling system. Sampling ports for turbidity, coliform bacteria, and Giardia cysts are shown on both the influent side and on the effluent side.

The contaminant injection port is comprised of a 0.64 cm (1/4 inch) diameter tube placed at the center of the 2.54 cm (1 inch) diameter influent pipe. The contaminants were injected at the center of the pipe. Four elbows were added to the piping after the point of contaminant injection to assure mixing prior to sampling of the contaminants on the influent side. The sampling of contaminants on the influent side was almost the same as the injection. The point of withdrawal was located 30 cm (12 inches) downstream from the last of the four elbows. The withdrawal tube was a 0.95 cm (3/8 inch) tube inserted to the center of the pipe. It was cut at 45° with the open side facing the flow. The purpose of this modification was to obtain a representative sample of contaminant concentration as it is fed to chemical pretreatment. This same modification for sampling was fabricated for the effluent side also. The point of effluent sampling was 122 cm (48 inches) downstream from the filter box. The stream sampled was pumped by positive displacement pump through a 293 mm diameter Nucleopore polycarbonate membrane filter, the device used to sample Giardia cysts. Coliform and turbidity samples were obtained from the influent side before connecting the membrane filter. On the effluent side, coliform and turbidity samples were taken from the discharge to the clear well.

OPERATION

The operation of the WATER BOY as it was set up and used at Colorado State University is described in the following sections. Instructions are summarized for the following steps: i) start up, ii) filtration, iii) backwashing, v) backwash flow control, v) filtration flow control, vi) chemical feed, vii) contaminant feed and sampling.

Start Up

i) Turn filter switch (on major control box) and backwash pump switch (minor control box) to off positions. The major and minor control boxes are shown in Figure D-7.

ii) Fill the rapid mix basin by turning on the raw water feed pump. Figure D-8 shows the raw water feed pump. Control raw water flow with the influent-flow-control-valve shown in Figure D-9.

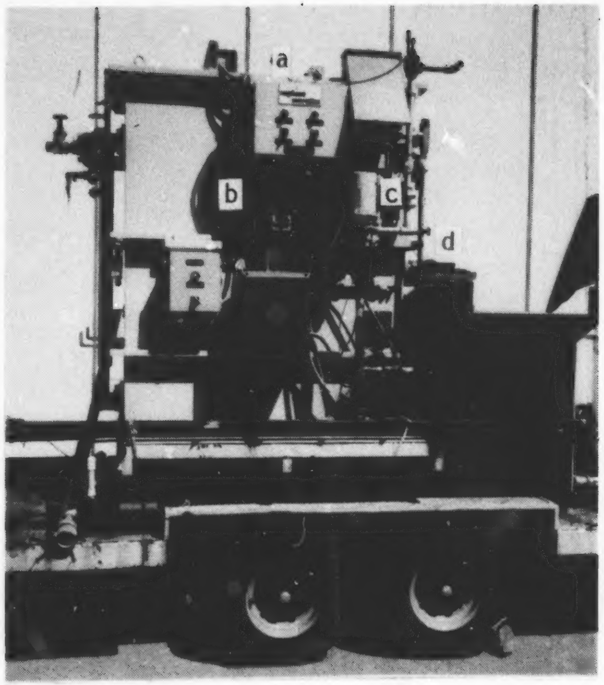


Figure D-7. Side view of WATER BOY: a) major control panel, b) minor control panel, c) effluent-flow pump, d) garden-hose-valve

Figure D-8. Raw water pump (1 1/2 hp)

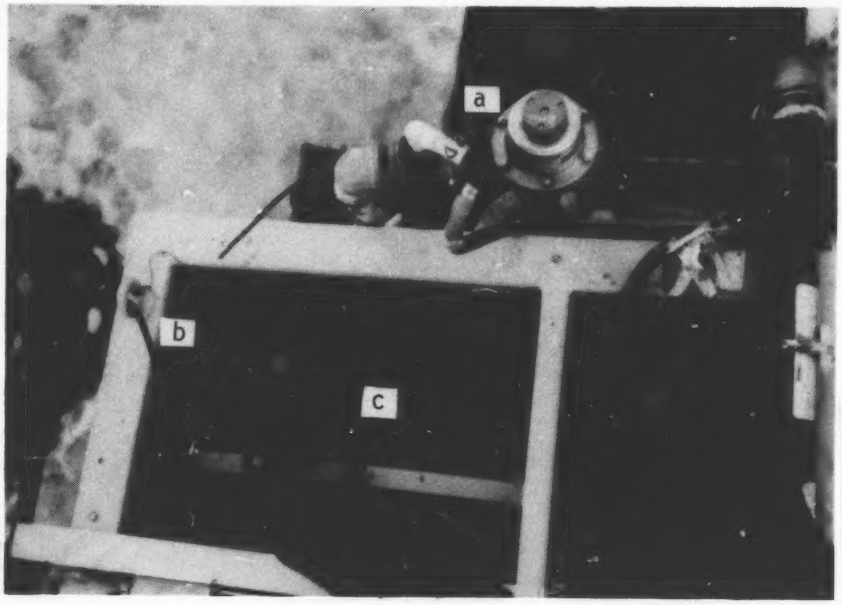


Figure D-9. Top view of rapid mix basin: a) influent-flow-control valve, b) mixer, c) rapid mix basin.

iii) Allow the water to overflow from the rapid mix basin into the filter box until the water level in the filter box is 10-12 cm above the filtration media; then turn off the raw water pump.

iv) Gently stir the filtration media (to a maximum depth of 50 cm) with a broom handle, or similar device, to remove the air bound within the filtration media.

v) After the bound air is removed, fill the filter box, by turning back on the raw water pump, to within 5 to 7 cm of the top, i.e. about 10 to 12 cm above the backwash overflow trough; then turn off raw water pump.

vi) Install the effluent-flow-control-float so the effluent-flow-control valve is about 90 percent open when the filter box is full. Figure D-10 shows the effluent-flow-control valve and the shaft of the float.

vii) Open garden-hose-valve on the effluent-side of the effluent-flow-pump. This primes the effluent-flow-pump, by using the available head within the filter box. Figure D-7 shows the garden-hose-valve, and the effluent-flow-pump.

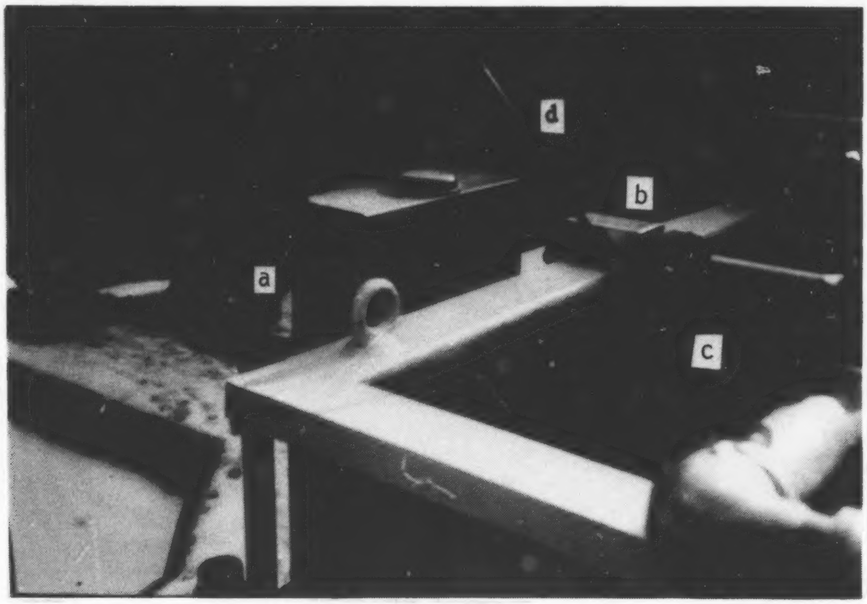


Figure D-10. Effluent flow control: a) effluent-flow-control valve, b) effluent-flow-pump-protector switch, c) shaft connected to effluent-flow-control-float, d) butterfly nut.

viii) Turn filter switch (on main control panel) to manual, green light should turn on. This activates the effluent-flow-pump and opens backwash valve #2.

ix) Turn on raw water pump. The effluent-flow-pump-protector-switch shown in Figure D-10 should be on, i.e. effluent-flow-pump should be on.

x) Adjust influent-flow-control-valve until an equilibrium is estabished within the filter box. Best operation is when the water level is 5 to 8 cm below the top of the filter box. This level can be varied by adjusting the fulcrum length on the effluent-flow-control-float by using the butterfly nut on its shaft. The butterfly nut is shown in Figure D-10.

xi) Once the system is running smoothly, allow it to filter water until the clear well is filled, i.e. about 45 minutes at 76 L/min (20 gpm). below).

xii) Once the clear well is filled, turn-off raw water feed pump and turn-off filter switch on main control panel. The clear well is the large cylindrical tank on the front of the WATER BOY®, and has an effective volume of 4000 liters.

xiii) Backwash the system to prepare the filtration media for a test run, following the backwashing procedures below.

Filtration

i) Prepare chemical feed and contaminant feed systems as described under the appropriate headings below.

ii) Turn-on the raw water pump, then immediately begin step iii) and step iv).

iii) Turn-on rapid mix basin mixer. Figure D-9 shows the 1/4 hp rapid mix basin mixer. This mixer must be plugged into electrical box No. 1 (left hand box as shown in Figure D-11) or an overloading of the circuit breakers will occur.

iv) Turn-on filter switch on main control panel to manual. Once the water level in the filter box raises high enough to activate the effluent-flow-pump-protector-switch, the green light on the main control panel will light indicating that the effluent-flow-pump is on. However, chemical and contaminant feed, and mixing, begin as soon as the filter switch is turned to manual even though the green light has not lit.

v) Adjust flow as described above in step x) of start up.

vi) Stop filtration by turning off raw water pump, filter switch, and rapid mix mixer.

Backwashing

i) Turn-off raw water feed pump, rapid mix mixer, and filter switch. This will automatically close backwash valve No. 2.

ii) Turn on backwash pump using switch on minor control box (directly below major control box). This will automatically open backwash valve No. 1.

iii) Slowly open backwash valve No. 3 (see Figure D-6). This allows the backwash pump to draw water from the clear well and pump it into the bottom of the filter.

iv) Check to insure that the water level in the filter box drops to the top of the overflow weir. If it does not, then either the backwash hose is clogged, possibly with ice, or more head is required between the backwash water discharge, i.e. disposal, point and the top of the overflow weir.

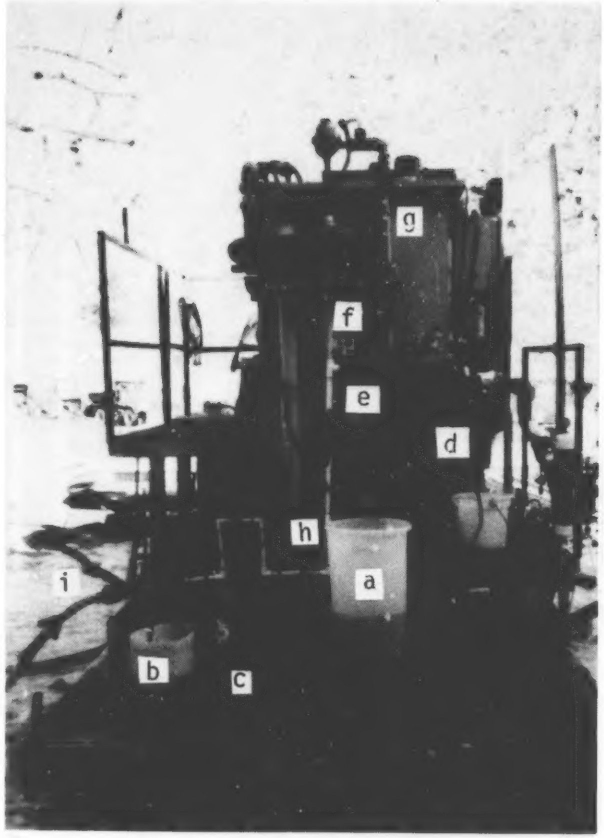


Figure D-11. Chemical feed system: a) polymer tank, b) alum tank, c) alum pump, d) polymer pump, e) electrical boxes, f) speed controller for polymer mixer, g) polymer injection port, h) alum injection port, i) influent raw water

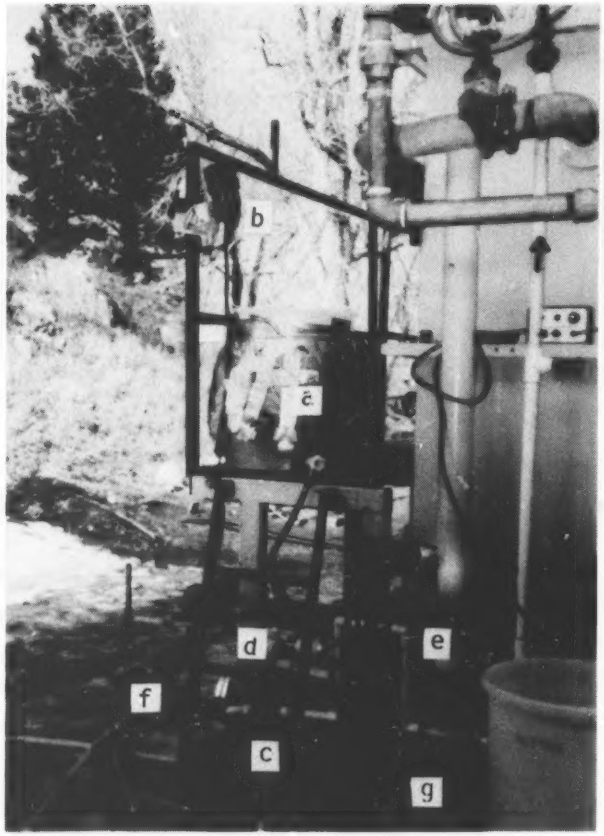


Figure D-12. Contaminant feed system: a) batch tank, b) mixer, c) injection port, d) metering pump, e) four elbows for mixing contminants with raw water, f) raw water influent line, g) influent sampling port for Giardia, coliforms, and turbidity

v) Stop the backwash cycle before the water level in the clear well reaches the pipe used by the backwash pump to draw the water from the clear well. This will prevent the backwash pump from pumping air.

vi) To stop the backwash cycle, turn off the backwash pump, and immediately close backwash valve No. 3. Close this valve _fast_, so that the filtration media "sets" properly.

vii) Filtration can now be resumed.

Backwash Flow Control

i) The backwash rate should be about 227 L/min (60 gpm), which is 10.2 mm/s (15 gpm/ft^2), which is 61 cm per minute rise within the filter box.

ii) The backwash rate can be adjusted by thottling backwash valve No. 4.

Filtration Flow Control

i) The influent flow is controlled by the influent-flow-control-valve.

ii) The effluent flow is controlled by the effluent-flow-control-float, which is connected to the effluent-flow-control-valve, which the effluent-flow-pump pumps against.

iii) The effluent-flow-pump is protected by the effluent-flow-pump-protector-switch, which is mounted at the top of the filter box and has two small floats attached to it. This protector switch automatically turns off the effluent-flow-pump when the water level in the filter box gets to low.

Chemical Feed

i) The chemical feed system is shown in Figure A-11.

ii) Both alum and polymer injection ports are injection quills which allow injection of the chemicals directly into the center of the flow stream.

iii) The following sample calculations illustrate how alum dosages were determined. Alum is reported as mg/L of $Al_2(SO_4)_3 \cdot 14H_2O$.

Given:
* Raw water flow rate = 75 L/min
* Alum solution feed rate = 15 mL/min
* Alum solution consists of 5 liters of distilled water and 500 mL of commerical grade liquid alum.

- There is 643 milligrams of $Al_2(SO_4)_3\ 14H_2O$ in every milliliter of commerical grade liquid alum.

Find: The dosage of alum in mg/L of $Al_2(SO_4)_3\ 14H_2O$ per liter of raw water.

Solution:

$$\frac{643 \text{ mg of } Al_2(SO_4)_3 \cdot 14\ H_2O}{\text{mL of soln}} \times \frac{500 \text{ mL of liquid alum}}{5.5 \text{ L of batch}} \times \frac{0.015 \text{ L of alum soln}}{\text{min}}$$

$$\times \frac{1 \text{ min}}{75 \text{ L raw water}} = \frac{11.5 \text{ mg of } Al_2(SO_4)_3\ 14H_2O}{\text{liter of raw water}}$$

iv) Polymer dosages were calculated as follows:

Given:
- Raw water flow rate = 75 L/min
- Polymer batch feed rate = 70 mL/min
- Polymer batch consists of 20 liters of tap water and 10 mL of polymer
- The specific gravity of the polymer is 1.14

Find: The dosage of polymer is milligrams of polymer per liter of raw water.

Solution:

$$\frac{1{,}140 \text{ mg of polymer}}{\text{ml of polymer}} \times \frac{10 \text{ mL of polymer}}{20 \text{ L of batch}} \times \frac{0.07 \text{ L of batch}}{1 \text{ min}}$$

$$\times \frac{1 \text{ min}}{75 \text{ l of raw waterL}} = \frac{0.5 \text{ mg of polymer}}{\text{liter of raw water}}$$

Contaminant Feed and Sampling

i) The contaminant feed system is shown in Figure D-12. Notice the four elbows which insure adequate mixing of the contaminants with the raw water prior to influent sampling.

ii) An injection quill, similar to the ones used for chemical feed, was used for injecting the contaminants. The contaminants consisted of raw water, dog feces, and primary effluent from Fort Collins Wastewater Treatment Plant No. 2. These contaminants were mixed in a 50 liter plastic batch tank, shown as a) in Figure D-12. The dog feces served as the *Giardia* cyst source, and the primary effluent was the coliform bacteria source.

iii) Figure D-6 shows the points in the flow scheme where the influent and effluent were sampled for turbidity, coliform bacteria, and *Giardia* cysts.

iv) Figure D-13 shows the *Giardia* sampling pump connected to the effluent *Giardia* sampling port. A representative effluent sample was obtained by placing the effluent sampling port in a 3.8 cm (1.5

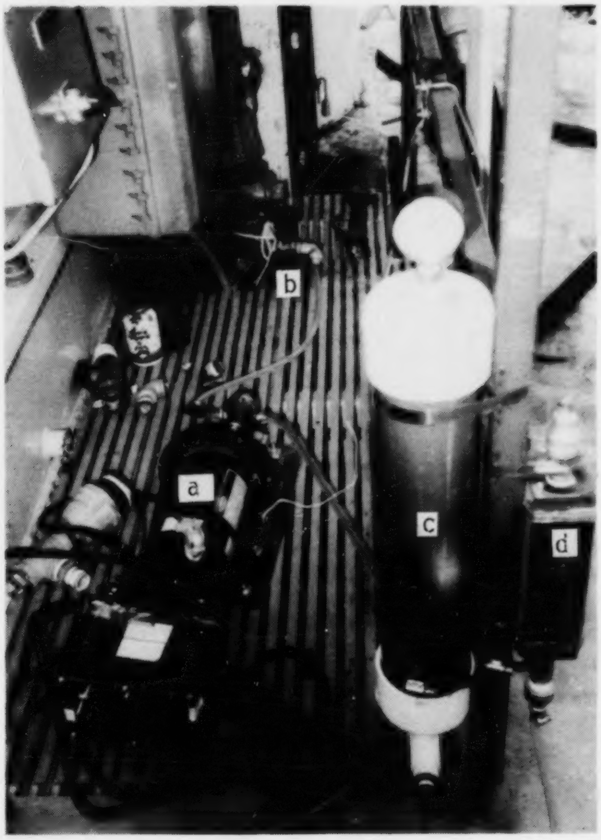


Figure D-13. Portion of apparatus for sampling *Giardia* cysts in effluent stream: a) *Giardia* sampling pump, b) effluent sampling port for *Giardia*, c) dampener to attenuate pressure fluctuations in the sampling stream, d) flow meter used to measure sampling flow rate.

inch) elbow, taking the sampling stream from the center of the pipe, and having the velocity of the sampling stream equal to the velocity of the main flow stream.

v) Representative influent sampling was insured by allowing streamlines direct access to the influent sampling port. This was obtained by having the water velocity in the sampling stream equal to the water velocity in the main flow stream, and by directing the sampling port towards the incoming flow.

APPENDIX E

DATA COLLECTION FORMS

Tables E-1 through E-6 were used during test runs using the laboratory-scale rapid rate filtration pilot plant to collect data for the different measurements and samples. Table E-1 shows an example of data collected from the milk cooler, used as a feed tank. The milk cooler was spiked, depending upon test run, with sewage and Giardia cysts, or with pure culture bacteria. Table E-2 is an example of data collected from the rapid mix basin and the filters; it shows also the results of sampling. Tables E-3 through E-6 are data forms used for recording analysis results from samples. Table E-7 illustrates the form used to record data obtained during test runs with the field-scale rapid rate filtration pilot plant.

Table E-1. Example of feed tank data obtained during test run using laboratory-scale rapid rate filtration pilot plant.

DATE 3/31/83 FEED TANK RUN NO. 107

Time	Volume (liters)	Temp (°C)	Turbidity (NTU)	Standard Plate Count (org/ml)	Total Coliform (org/100ml)	*Giardia* Cyst (cyst/l)	Notes
900	370	3	0.57 CLP 0.68				0.57NTU before Giardi cyst added
1100	312		0.68				0.68 after G. cyst added and 500 ml sewage.
1145	295	3	0.68	30500	10	2750 cyst / 9.22L	CLP: Cache La Poudre river
							Design G. cyst/L
1300			0.68				is 44000 cy/L in the tank.
1410	195	3	0.68				

Table E-2. Example of data collection during test run for laboratory-scale rapid rate filtration pilot plant.

DATE 3/31/83 RAPID SAND FILTER RUN NO. 107

TIME	PUMP			FILTER NO. 3 Dual media Diameter 10cm F.C. Sand					Alum Conc. 10/990 ml		572C Conc. 1ml/liter		Rapid Mix		Filter Effluent			
	Flow Rate (ml/min)	Setting	Pressure (psi)	Temp. °C	Pressure (psi)	D-Pressure (Hg/cm)	Flow Rate (ml/min)	Turbidity (NTU)	FLow Rate (ml/min)	Setting	Flow Rate (ml/min)	Setting	RPM	Temp.	Standard Plate (org/ml)	Total Coliform (org/100 ml)	Giardia (cysts/l)	NOTES
945	680	6	3.7	1	1.5	2.7	680	0.42	0		0		500	1				
1030			3.9	4	1.5	3.5		0.11	1	0.5	0.34	0.1						
1110	680	6	3.9	4	1.6	3.7	680	0.05	1.2	0.5	0.34	0.1		3				
1115						Back wash												
1130	680	6	3.5	4	1.4	2.8	680	0.99	1.2	0.5	0.34	0.1		4				
1138			4	5	3	3.0		1.22	1.2	0.5	0.34	0.1			2300	1	20 cyst / 20.4 L	start Ga dia Sampl
1210			4	4	1.5	3.0		0.22	1.2	0.5	0.34	0.1						stop A Start B
1300			4.2	4	2	3.4	680	0.05	1.3	0.5	0.33	0.1		4	1000	1		
1410	680	6		4	2	3.5	680	0.07	1.3	0.5	0.33	0.1		4			20 cysts / 81.6 L	stop B on the run test

Table E-3. Standard plate count bacteria data obtained during analysis of samples taken during operation of laboratory-scale rapid rate filtration pilot plant.

STANDARD PLATE COUNT BACTERIA
ANALYSIS SHEET
(RAPID RATE FILTRATION)

RUN NUMBER	SAMPLE NUMBER	ANALYSIS START		DILUTION	COUNT (colonies) AT INCUBATION (hr)				RESULTS REPORTED (no./ml)	ANALYSIS BY (initials)	COMMENTS
		TIME	DATE		24	48	72	96			
107	TANK Sample A	1400	3/31	0.001		32			35,000	RCW	
				0.001		38					
				0.01		41					
				0.1		139					
107	TANK Sample B.	1400	3/31	0.001		30			26,000	RCW	
				0.001		22					
				0.01		TNC					
				0.01		TNC					
107	Filter 3 sample A	1400	3/31	0.01		23			2,300	RCW	
				0.1		212					
				0.1		725					
				1		TNC					
107	Filter 3 Sample B	1400	3/31	0.01		17			1,00	RCW	
				0.1		715					
				0.1		91					
				1		TNC					
				1		TNC					

Table E-4. Total coliform bacteria data obtained during analysis of samples taken during operation of laboratory-scale rapid rate filtration pilot plant.

TOTAL COLIFORM BACTERIA
ANALYSIS SHEET
(RAPID RATE FILTRATION)

RUN NUMBER	SAMPLE NUMBER	ANALYSIS START		DILUTION	COUNT (colonies) AT INCUBATION (hr)				RESULTS REPORTED	ANALYSIS BY	COMMENTS
		TIME	DATE		24	48	72	96	(no./100ml)	(initials)	
107	TANK	1400	3/31	0.1	0				10	RCW	
				1	0						
				1	0						
				10	1						
				10	1						
107	TANK Sample B	1400	3/31	0.1	0				10	RCW	
				1	0						
				1	0						
				10	2						
				10	1						
107	Filter3 Sample A	1400	3/31	10	1				1	RCW	
				10	0						
				100	0						
				100	0						
				100	1						
107	Filter3 Sampel B	1400	3/31	10	0				1	RCW	
				10	0						
				100	1						
				100	1						

Table E-5. Particle count data obtained during analysis of samples taken during operation of laboratory-scale rapid rate filtration pilot plant.

PARTICLE COUNT RESULTS

Date 3/31/83
Sample Rate

	Run No. 107 Sample No. TANK				Run No. 107A Sample No. Filter 3			
Ch	Bkgnd. Count	Count	Net Count	Count (No./10ml)	Bkgnd. Count	Count	Net Count	Count (No./10ml)
1	—	—			—	—	—	—
2	—	—			—	—	—	—
3	298	25022	24724	35266	298	651	353	504
4	125	10042	9917	14145	125	287	162	231
5	104	4468	4364	6225	104	150	46	66
6	53	1547	1494	2131	53	85	32	46
7	29	522	493	703	29	37	8	11
8	8	207	199	284	8	17	9	13
9	3	92	89	127	3	16	13	19
10	5	53	48	68	5	4	—	—
11	0	21	21	30	0	9	9	13
12	1	11	10	14	1	3	2	3
13	1	6	5	7	1	3	2	3
14	1	3	2	3	1	10	9	13
15	1	1	0	0	1	12	11	16
16	0	3	3	4	0	43	43	61
Time	100	100						

	Run No. 107B Sample No. Filter 3				Run No. Sample No.			
Ch	Bkgnd. Count	Count	Net Count	Count (No./10ml)	Bkgnd. Count	Count	Net Count	Count (No./10ml)
1	—	—	—	—				
2	—	—	—	—				
3	298	1454	1156	1649				
4	125	760	635	906				
5	104	433	329	469				
6	53	242	189	270				
7	29	138	109	155				
8	8	81	73	104				
9	3	33	30	43				
10	5	17	12	17				
11	0	4	4	6				
12	1	2	1	1				
13	1	0	—	—				
14	1	0	—	—				
15	1	0	—	—				
16	0	0	0	0				
Time								

$$\frac{\text{Count}}{10\text{ml}} = \frac{\text{Count} \times 10\text{ml}}{\text{Time} \times \text{Flow}} \times \frac{222\text{ ml}}{207\text{ ml}} = \frac{(X) \times 10}{100 \times \underset{26.6}{\underline{2}}} \times \frac{222}{207} =$$

Time in sec., Flow in ml/sec.

WDB 3-82

Table E-6. Giardia cyst data obtained during analysis of samples taken during operation of laboratory-scale rapid rate filtration pilot plant.

GIARDIA QUANTITATION

Filtration System RAPID SAND

Run Information (sample label)	Analysis Date	amt. conc. in sample	Analysis by	Counts of Replicates	Cyst # Reported	Observations and Comments
Run 106 TANK	4-4	—	DGH 1200	1:5 1200 1400	1300	typical tank w/ decreased debris
Run 106 Filter 3	4-4	—	DGH	1:1 1440 1600	1520	algae fairly clean cysts are in good condition.
Run 107 TANK	4-4	—	DGH	1:5 2600 2900	2750	cysts in good condition typical tank w/ increase in amt of small debris
Run 107 A Filter 3	4-4	—	DGH	1:1 0	<20	see below
Run 107 B Filter 3	4-4	—	DGH	1:1 0	<20	DE diatoms Very clean

Table E-7. Sample data sheet for field-scale pilot plant.

Time	Turbidity (NTU) Inf	Turbidity (NTU) Eff	Diff. Head (ft. of HOH)	Poly tank reading(liters)	Poly feed rate(ml/min)	Alum tank reading(liters)	Alum feed rate(ml/min	Spike tank reading(liters)	Spike feed rate(ml/min)	Flow meter reading(cu. ft)	Plant flowrate(gpm)	water temperature	COMMENTS
0:25				50				40					Start Flow & Feed Pumps
0:30			.8							368			WB#2 taken (Eff coliform)
0:35	6.5											12°C	WB#3
0:40													WB#4
0:55		1.1											WB#5 & WB#6
1:00			1.2									12°C	Start sampling for inf cysts
1:06													Stop sampling for inf cysts
1:25	6.5	1.0											Start sampling for eff cysts
1:35										559	22		WB#7
1:45			1.3	45.5	65			25	210				Stop sampling for Eff cysts

Date: 7/13/83 Run#: 59 Polymer Used: 8102

Polymer Batch Mix: $\frac{100\,ml}{50\,l}$ Alum Batch Mix: Ø

Giardia Batch Mix: (3.6x10^6 cysts & 3 l of primary eff)/4.0 l

Type of Filtration: IN-LINE

Type of Water: HT Avg. Plant flow rate (gpm): 22

Purpose of Run: Above opt Giardia Removal, & coliform conc vs. time

Avg. poly feed rate (ml/min): 65

Avg. Alum feed rate (ml/min): Ø

Inf Coliform Count (#/100ml): 1200

Eff Coliform Count (#/100ml): @1 Hr = 20

Inf Giardia Count (cysts/liter): JMG#13 (12 gal) 25

Eff Giardia Count (cysts/liter): JMG#14 (40 gal) Zero

Calculations:

WB - coliform samples
JMG - GIARDIA SAMPLES

$$DCC = \text{DESIGNED cyst conc} = \frac{(3.6\times10^6)\,.21}{40}\,\frac{1}{(22)3.785} = \boxed{210\ \text{cyst/liter}}$$

$$\text{Poly Feed} = \frac{(65)\left(\frac{100}{50}\right)}{(2.2)3.785} = 11\ \text{mg/l}$$

MMENTS: pH of RAW WATER = 6.6
WB#1 IS PURE primary eff.; WB#6 IS inf SAMPLE

APPENDIX F

STATISTICAL ANALYSIS OF DATA

The statistical analyses conducted were advised by Professor Hariharan K. Iyer, Department of Statistics, Colorado State University (the authors assume responsibility for any misinterpretation of Professor Iyer's advice).

The designations for the statistical analysis techniques used include: (1) trend of relationship between variables, (2) correlation analysis, (3) significance of the association and (4) probability of occurrence. These techniques are described in the following paragraph.

TREND OF VARIABLES

In order to show the trend of the relationship between two variables the median for each variable for each group of points was calculated. The median of the first few points in ascending data, was obtained first. This was followed by obtaining the median of second few points, and so on. These medians thus showed the overall trend in the data. Figure F-1 shows the trend of scattered data by connecting the median points.

Example

Consider Figure F-1. The figure shows a plot of the percentage removal of Giardia cysts, versus percentage removal of turbidity. The total number of data are seventy two points. Picking first 8 points from left to right, compute the medians of these 8 points for turbidity, and also the 8 points for Giardia. Then plot the median. Continue and plot the median for the second group of 8 points of data, and calculate the median for both turbidity and Giardia as before. Continue for third group, the fourth group, etc. Connect these median points by a line to show the general trend of data.

CORRELATION ANALYSIS

Correlation analysis provides a statistical summary of the strength of association between variables. The method, described as the Spearman method, first ranks the data used to calculate the correlation coefficients. The coefficient varies from - 1.0 to + 1.0. A coefficient of 0 always indicates that no monotone relationship exists. A coefficient of 1.0 implies a "perfect" positive monotone relationship. A coefficient of - 1.0 indicates a "perfect" negative monotone relationship. Thus to prove there is positive association between two variables, the coefficient should range from zero to + 1.0.

A computer package (Minitab), available on the CSU Cyber 720 can be used to compute the correlation coefficient, r_s. The Spearman equation for computing r_s is:

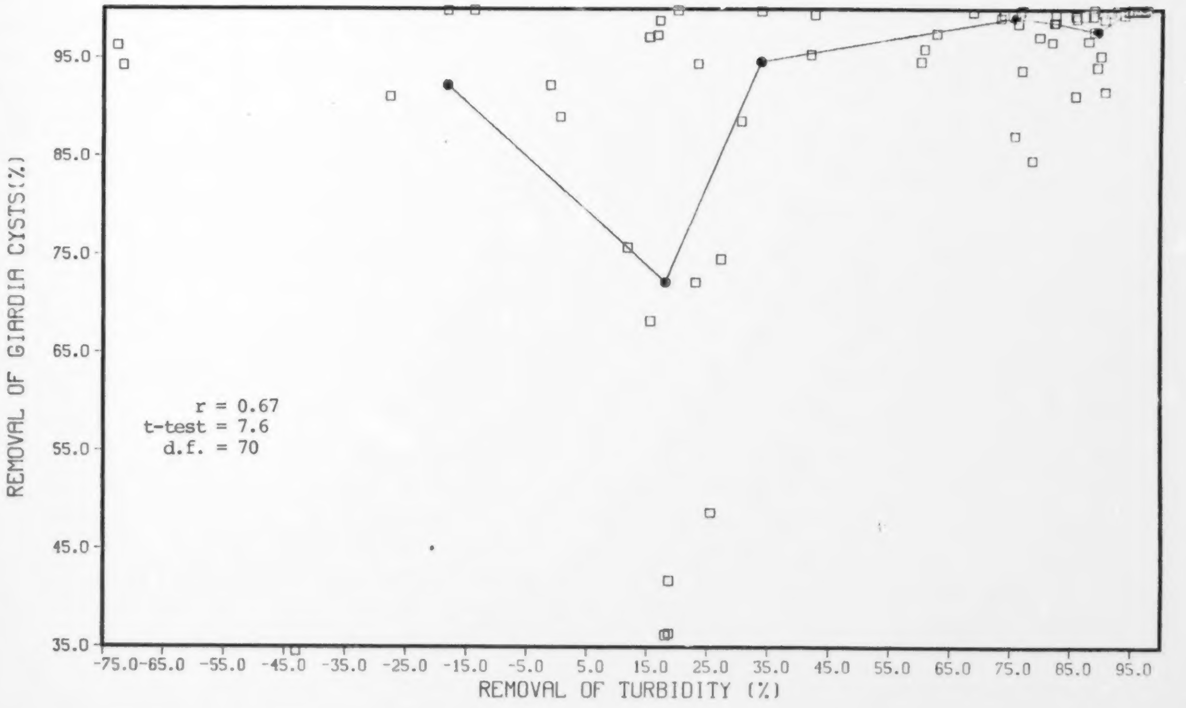


Figure F-1. Observations of percent removal of Giardia cysts with corresponding percent removal of turbidity. Data obtained from Table A-1 and Table A-2. The solid points show the median for each 8 points, connected by line.

$$r_s = 1 - \frac{6 \sum_{i=1}^{n} d_i^2}{N^3 - N}$$

where d = difference between ranks of corresponding pairs of the two variables, and

N = number of observations

The Spearman correlation coefficient for the data shown in Figure F-1 is 0.673. This implies a positive relationship between the percent of turbidity removed and percent of Giardia cysts removed. Thus when a higher percent removal occurs for turbidity, a higher percent removal of Giardia cysts is expected.

SIGNIFICANCE OF ASSOCIATION

The significance of the "association" correlation coefficient, r_s, data is determined by comparing the quantity, t, as defined,

$$t = r_s \frac{N - 2}{1 - r_s^2}^{1/2}$$

with student's t-distribution with N-2 degrees of freedom.

Example

The computed t for data figure 1 is 7.612. This compared with a value 2.65 from t-distribution table (for one tail) at level of significance of 0.005 for 70 degrees of freedom . Therefore we accept the hypothesis of positive association at 0.995 level of confidence.

Probability of Occurrence

A complementary probability method is used to predict the "probability of occurence" of certain levels of removal. Figure F-1 shows the percentage removal of Giardia cysts vs percentages removal of turbidity. The probability of removal of certain level of Giardia cysts due to the removal of certain levels of turbidity is predicted by using a complementary method. To determine the probability of the percent of Giardia removed when 80 percent or more of turbidity removed is predicted as follows. (1) Pick all the points which give 80 percent or more of turbidity removal and put these points in two columns. The right column is percent removal of Giardia cysts, ranked in ascending order; the left column is the percent removal of the associated turbidity values. Table F-1 illustrates, using the data shown in Figure F-1. There are 35 points. Calculate the estimated probability as first point as 35/36, the second point as 34/36, the third point as 33/36 and so on; the last point is 1/36. These probability numbers are in a fourth column in Table F-1, to the right of the Giardia data. Then draw the

Table F-1. Showing an example of calculating an estimated probability.

Point Number	% Removal Turbidity	% Removal Giardia	Estimated Probability
1	86.00	91.250	0.9999
2	90.79	91.690	0.9714
3	89.47	94.150	0.9429
4	90.00	95.320	0.9143
5	82.03	96.720	0.8857
6	88.00	96.850	0.8571
7	80.00	97.240	0.8286
8	88.89	97.770	0.8000
9	82.41	98.700	0.7714
10	90.63	99.060	0.7429
11	86.11	99.130	0.7143
12	87.50	99.370	0.6857
13	88.68	99.380	0.6571
14	85.94	99.390	0.6286
15	82.61	99.470	0.6000
16	93.85	99.480	0.5714
17	91.67	99.740	0.5429
18	19.20	99.750	0.5143
19	94.55	99.810	0.4857
20	95.20	99.870	0.4571
21	97.11	99.900	0.4286
22	96.70	99.900	0.4000
23	94.21	99.910	0.3714
24	92.65	99.920	0.3429
25	96.84	99.940	0.3143
26	95.03	99.950	0.2857
27	95.91	99.950	0.2571
28	88.89	99.960	0.2286
29	97.60	99.970	0.2000
30	96.00	99.970	0.1714
31	95.00	99.970	0.1429
32	94.95	99.970	0.1143
33	95.45	99.980	0.0857
34	97.20	99.990	0.0571
35	96.36	99.990	0.0286

estimated probability of occurence of a given percent removal of Giardia cysts, designated as "estimated probability" in the ordinate, vs Giardia cysts removal percentage on the abcissa, as shown in Figure F-2. To read the graph, consider the question of finding the probability of 95 percent Giardia cysts removal when turbidity removal is 80 percent. The procedure as follows: (1) Enter the abcissa at 95 percent of Giardia cyst removal, (2) using the 80 percent turbidity removal curve, read the corresponding estimated probability of occurence that Giardia removal is 93 percent. Thus if turbidity removal is 80 percent, the estimated probability is 93 percent that Giardia cyst removal is 95 percent.

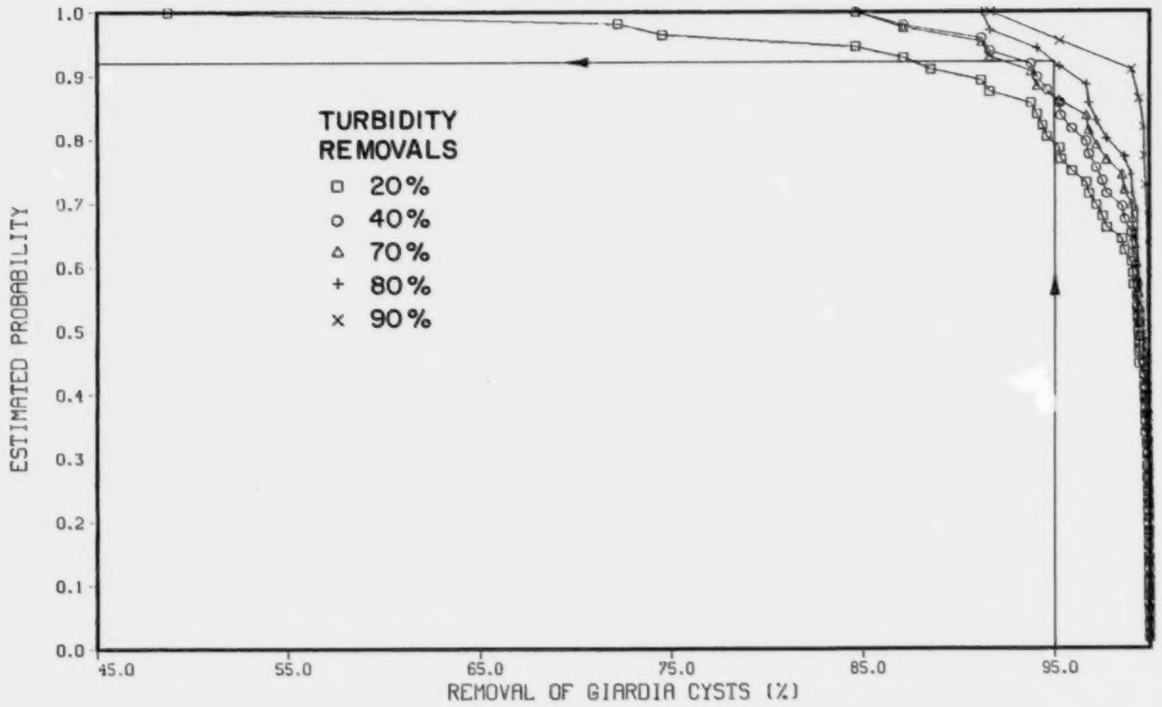


Figure F-2. Probability of a given percent removal of Giardia cysts for specified percent removals of turbidity. Data obtained from Table A-1 and Table A-2 plotted in Figure E-12.

APPENDIX G

SUPPORTING GRAPHS

In analysis of the results, contained in Table A-1, a large number of plots were generated. Because it would be to repititious to include all of them in the text, they are placed here for reference. In addition, some were used as the basis for developing plots and tables to show information in alternative ways, e.g. three-dimensional histograms.

Test Conditions

Run number(s)	: 157,158,160
Raw water turbidity	: 0.45 NTU
Temperature	: 7C
Primary coagulant	: Run 157 1.0 mg/l 572C. Run 158 5.4 mg/l alum. Run 159 4.3 mg/l 572C + 4.3 mg/l alum.
Secondary coagulant	: Run 157 9.0 mg/l alum. Run 158 0.5 572C.

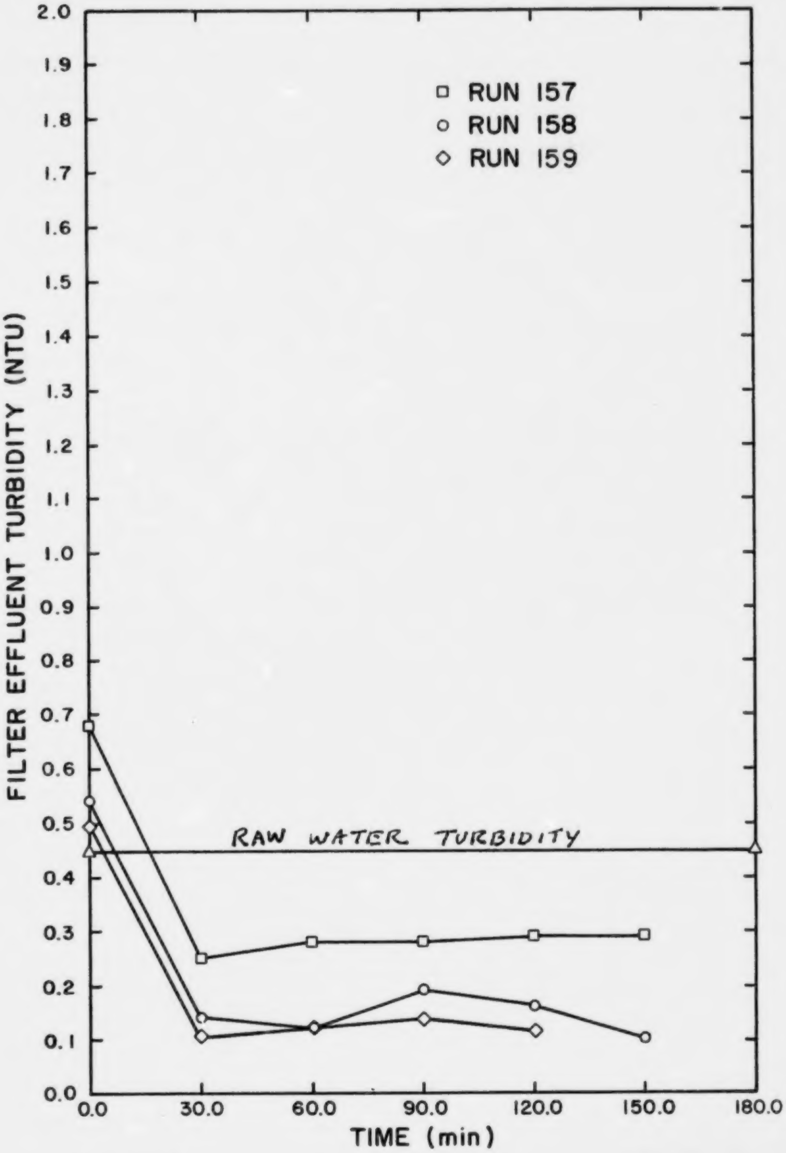


Figure G-1. Effect of sequence of alum-polymer additions on effluent turbidity, laboratory-scale pilot plant using dual media with Fort Collins sand, artificial low turbidity water from Horsetooth Reservoir, and "in-line" filtration.

Test Conditions
Run number(s) : 152,154,155
Raw water turbidity : 0.45 NTU
Temperature : 18C
Primary coagulant : Run 152 0.7 mg/l alum + 1.9 mg/l 572C.
Run 154 0.9 mg/l alum, Run 155 0.5 mg/l 572C.
Secondary coagulant : Run 154 0.5 mg/l 572C, Run 155 1.4 mg/l alum.

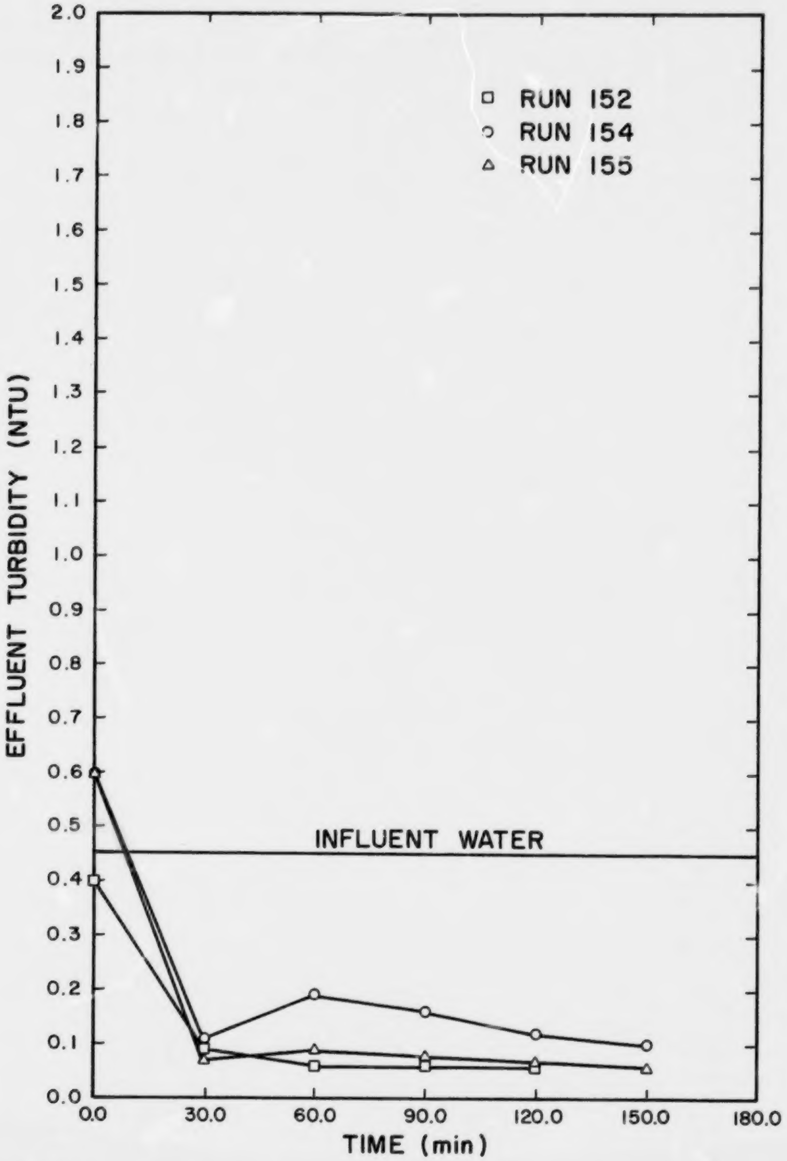


Figure G-2. Effect of sequence of alum-polymer additions on effluent turbidity, laboratory-scale pilot plant using dual media with Fort Collins sand, artificial low turbidity water from Horsetooth Reservoir and "in-line" filtration.

Test Conditions
Run number(s) : 146 "in-line", 147 direct filtration
Raw water turbidity : 0.89 NTU
Temperature : 3.5C
Primary coagulant : Run 146, and Run 147 9.32 mg/l alum.
Secondary coagulant : Run 146, and Run 147 0.35 mg/l 572C

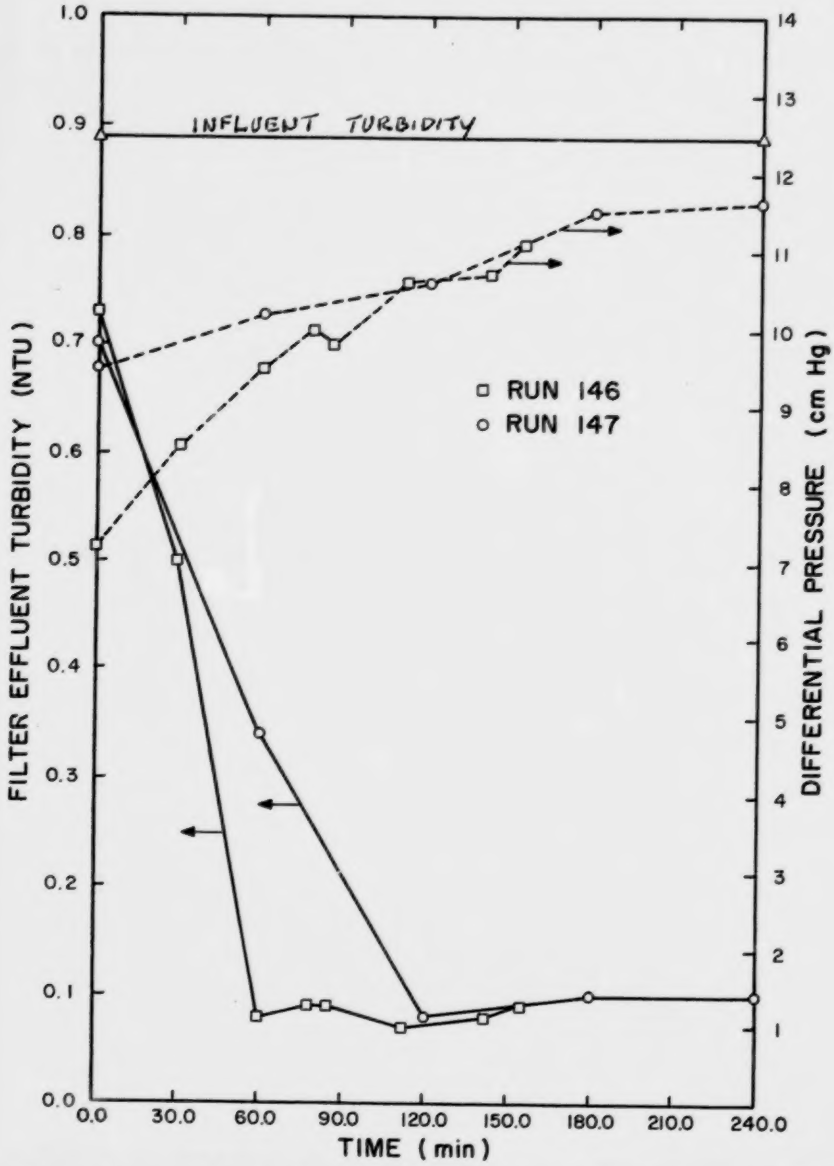


Figure G-3. Comparison of turbidity and headloss for "in-line" and "direct" filtration laboratory-scale pilot plant using dual media Fort Collins sand, artificial low turbidity water from Horsetooth Reservoir.

Test Conditions

Run number(s)	: 76 single, 77 dual media
Raw water turbidity	: 0.49 NTU
Temperature	: 3C
Primary coagulant	: none
Secondary coagulant	: none

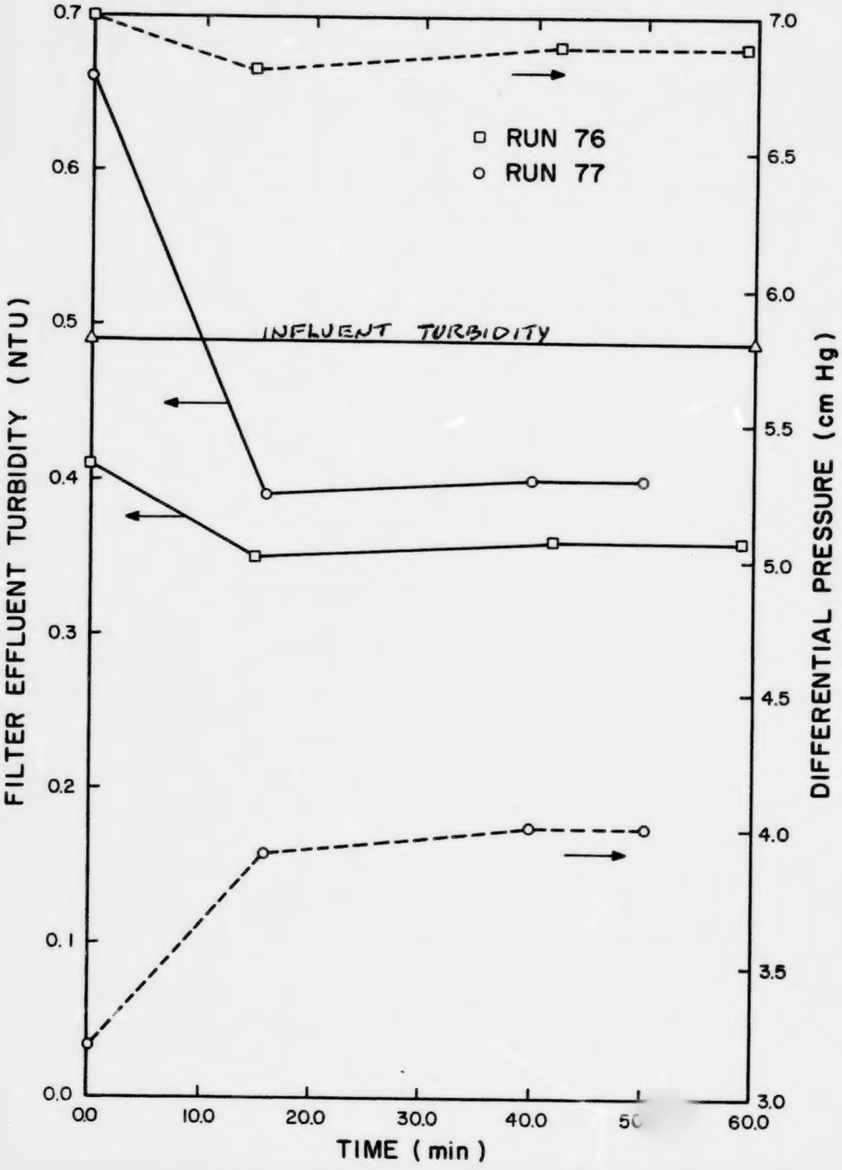


Figure G-4. Comparison of turbidity and headloss for single and dual media of Loveland sand, wth no chemical pretreatment. Laboratory-scale using artificial low turbidity water from Horsetooth Reservoir, and "in-line" filtration.

Test Conditions
Run number(s) : 71 sand, 72 dual media.
Raw water turbidity : 0.96 NTU
Temperature : 3C
Primary coagulant : Run 71 15 mg/l alum. Run 72 16.6 mg/l alum.
Secondary coagulant : Run 71 1.3 mg/l 572C. Run 72 1.3 mg/l 572C.

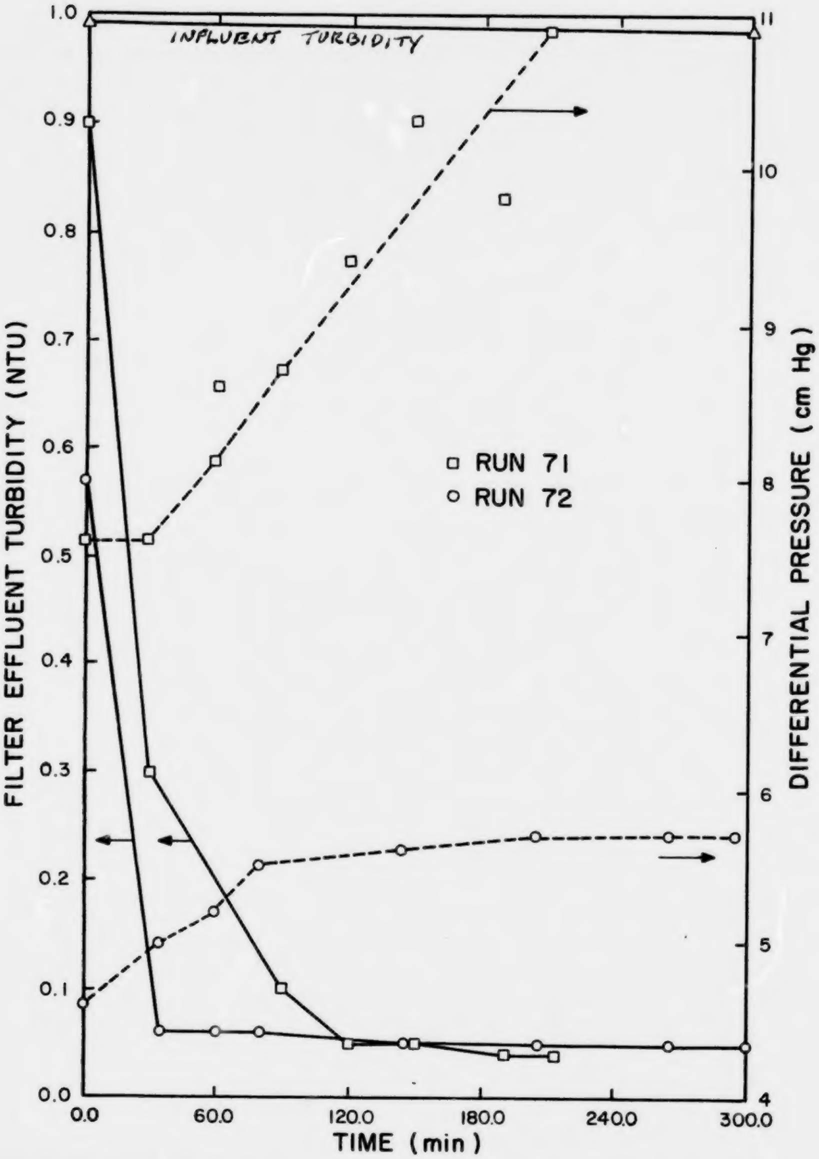


Figure G-5. Comparison of turbidity and headloss for single and dual media of Loveland sand, with optimum chemical pretreatment. Laboratory-scal pilot plant, using artificial low turbidity water from Horsetooth Reservoir and "in-line" filtration.

Test Conditions
Run number(s) : 98 sand, 99 dual media
Raw water turbidity : 2.4 NTU
Temperature : 3C
Primary coagulant : Run 98 8.79 mg/l 573C
Run 99 7.46 mg/l 573C
Secondary coagulant : Run 98 none. Run 99 none.

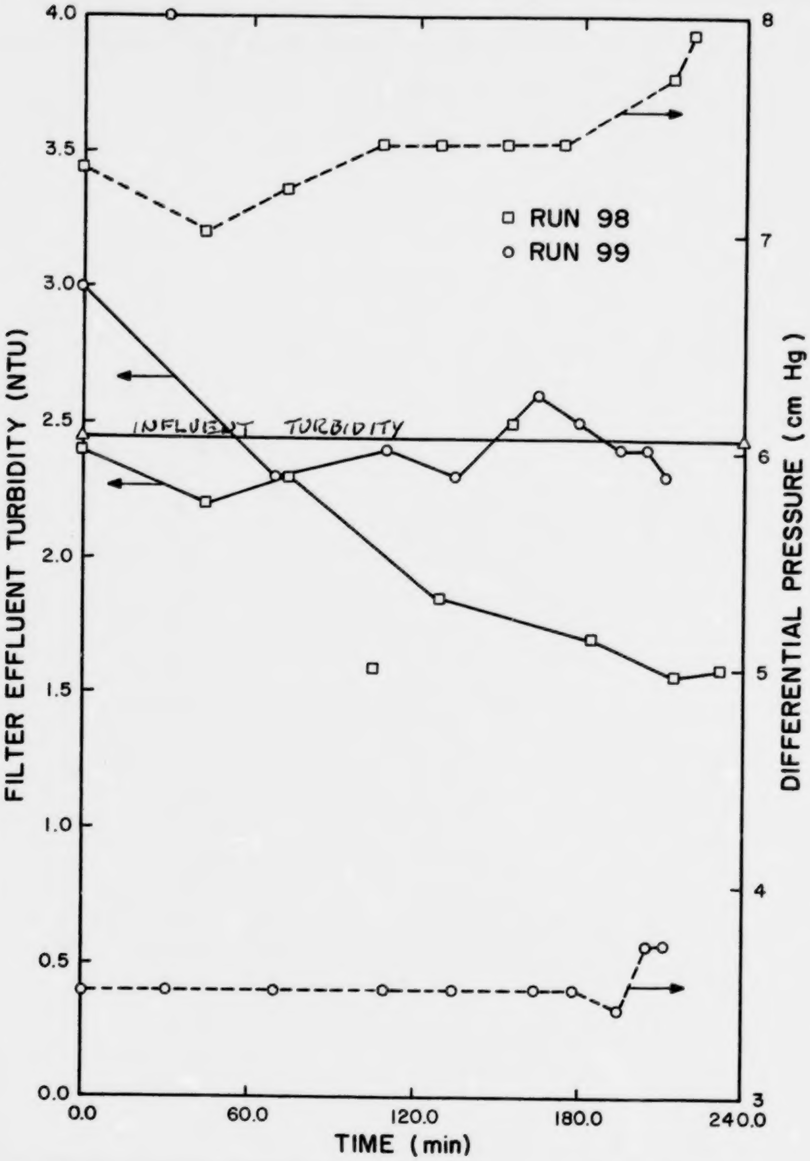


Figure G-6. Comparison of turbidity and headloss for single and dual media of Loveland sand, with alum pretreatment. Laboratory-scale pilot plant using artificial low turbidity water from Horsetooth Reservoir and "in-line" filtration.

Test Conditions

Run number(s) : 151,159
Raw water turbidity : 0.45 NTU
Temperature : Run 151, 18C, Run 159, 4C
Primary coagulant : Run 157 and Run 159, 0.42 mg/L 572C

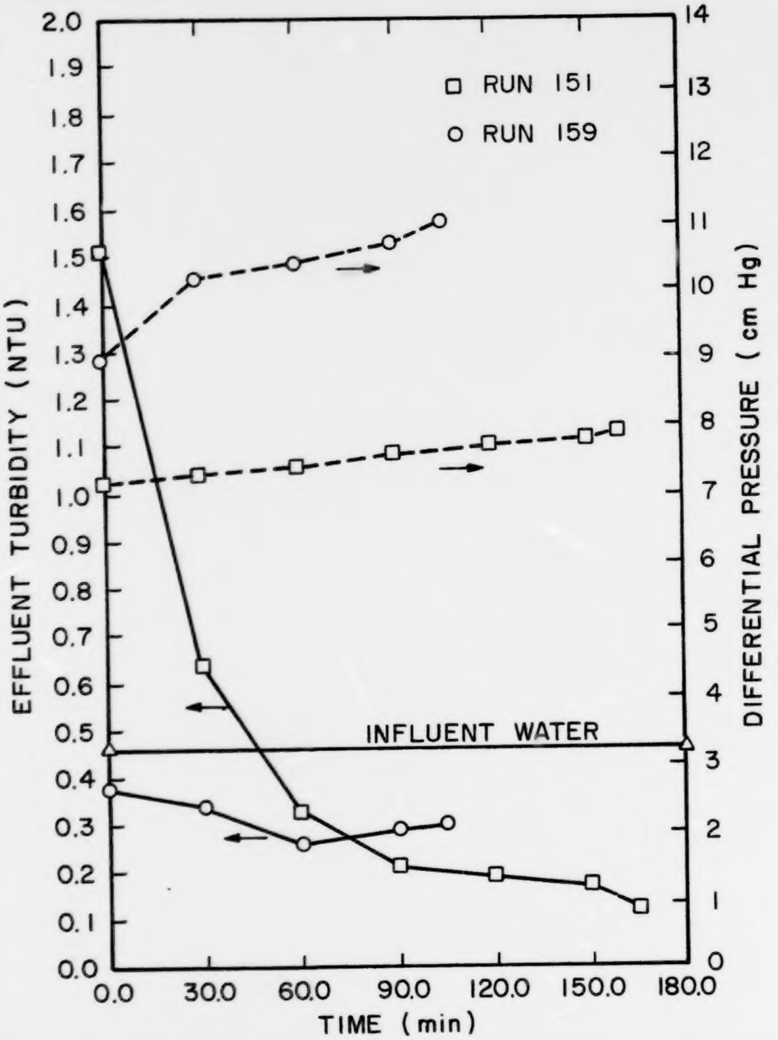


Figure G-7. Effluent turbidity and headloss versus time, showing the effect of temperature on turbidity reduction, and headloss.

Test Conditions
Run number(s) : 152,160
Raw water turbidity : 0.45 NTU
Temperature : Run 152, 18C, Run 160, 4C
Primary coagulant : Run 152 and Run 160, 4.31 mg/L alum + 1.85 mg/L 572C

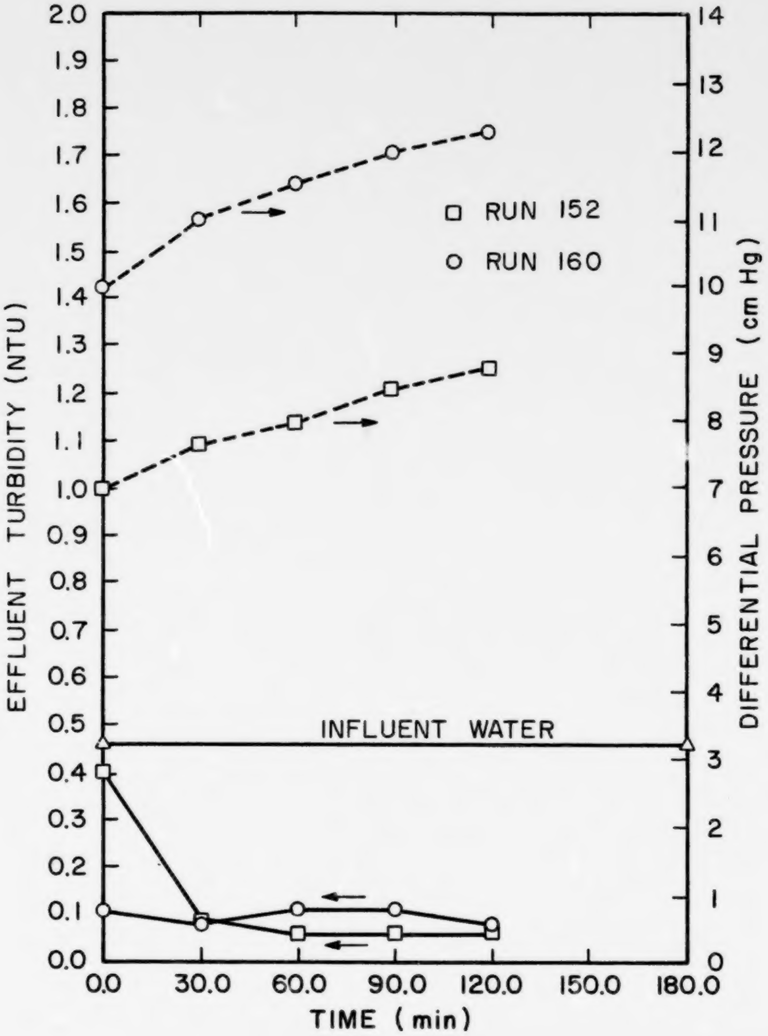


Figure G-8. Effluent turbidity and headloss versus time, showing the effect of temperature on turbidity reduction and headloss for adding alum and Magnifloc 572C in the same basin.

Test Conditions
Run number(s) : 154,158
Raw water turbidity : 0.45 NTU
Temperature : Run 154, 18C, Run 158, 4C
Primary coagulant : Run 154 and Run 158, 0.5 mg/L polymer

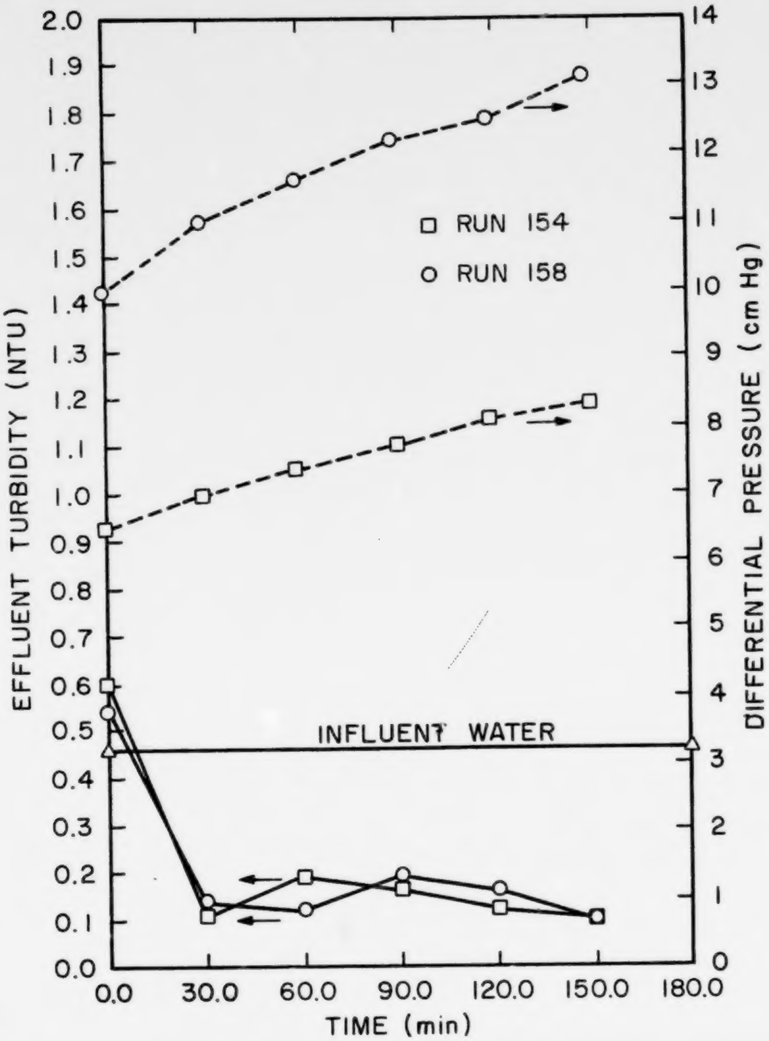


Figure G-9. Effluent turbidity and headloss versus time, showing the effect of temperature on turbidity reduction and headloss when alum was added and then Magnifloc 572C in two coagulant basins.

Test Conditions

Run number(s)	: 155,157
Raw water turbidity	: 0.45 NTU
Temperature	: Run 155, 18C, Run 157, 4C
Primary coagulant	: Run 155 and Run 157, 9 mg/L alum

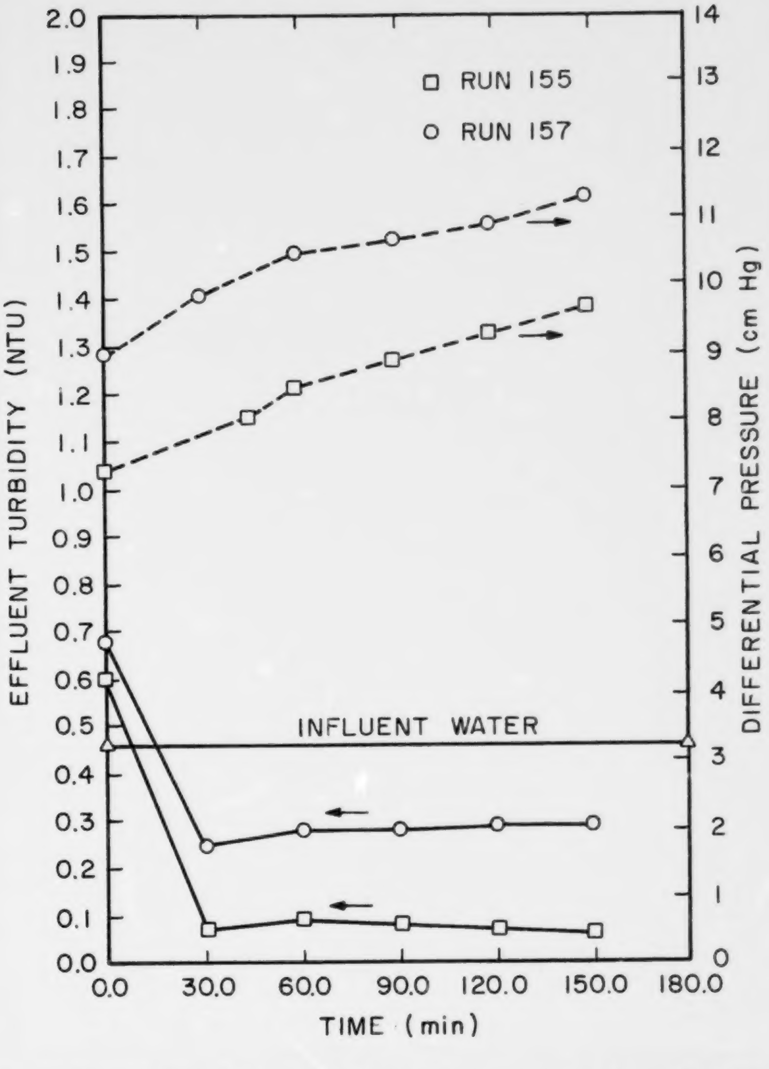


Figure G-10. Effluent turbidity and headloss versus tim, showing the effect of temperature on turbidity reduction and headloss when Magnifloc 572C was added before alum in two coagulant basins.

Test Conditions
Run number(s) : 150,151
Raw water turbidity : 0.45 NTU
Temperature : 18C
Coagulant : Run 150, 5.8 mg/L alum alone

Coagulant : Run 151, 0.42 mg/L 572C alone

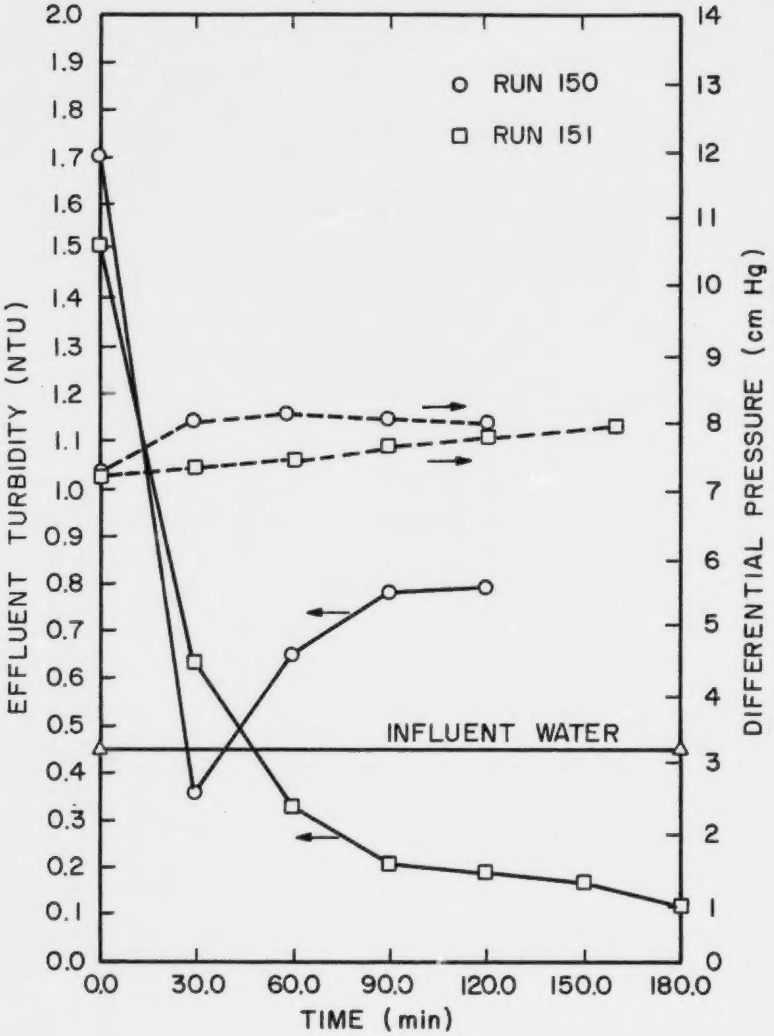


Figure G-11. Effluent turbidity versus time, showing the effect of turbidity reduction and headloss of using alum alone or Magnifloc 572C alone.

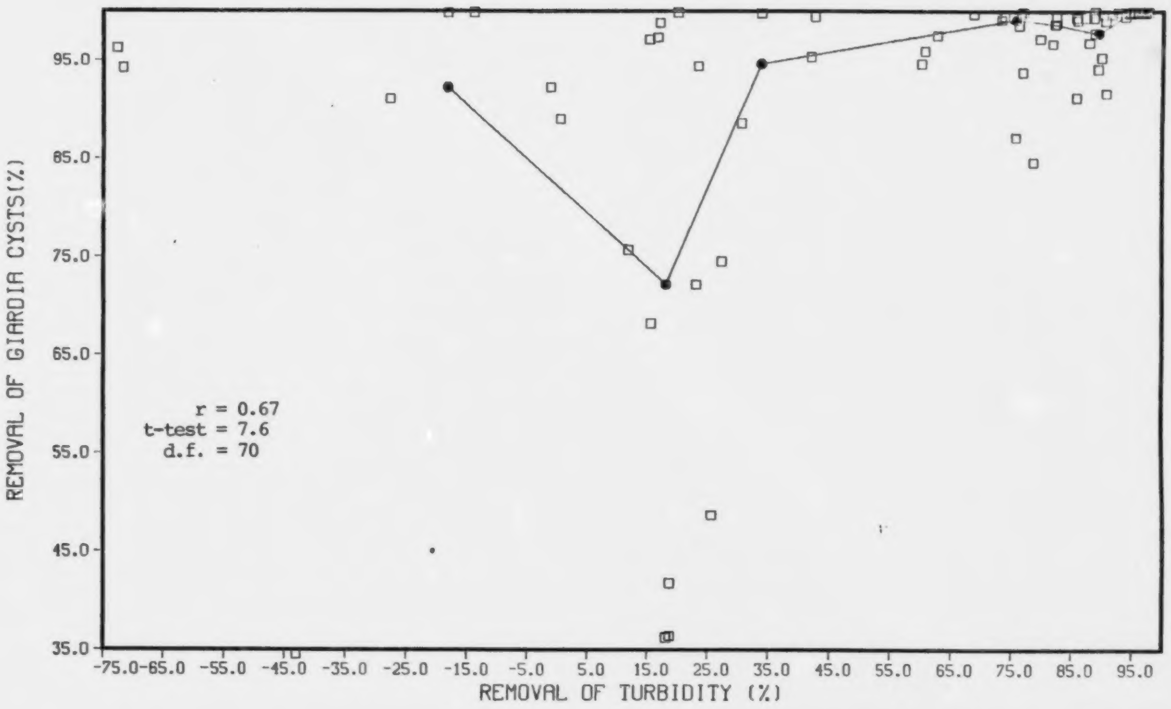


Figure G-12. Observations of percent removal of Giardia cysts with corresponding percent removal of turbidity. Data obtained from Table A-1 and Table A-2. The solid points show the median for each 8 points, connected by line.

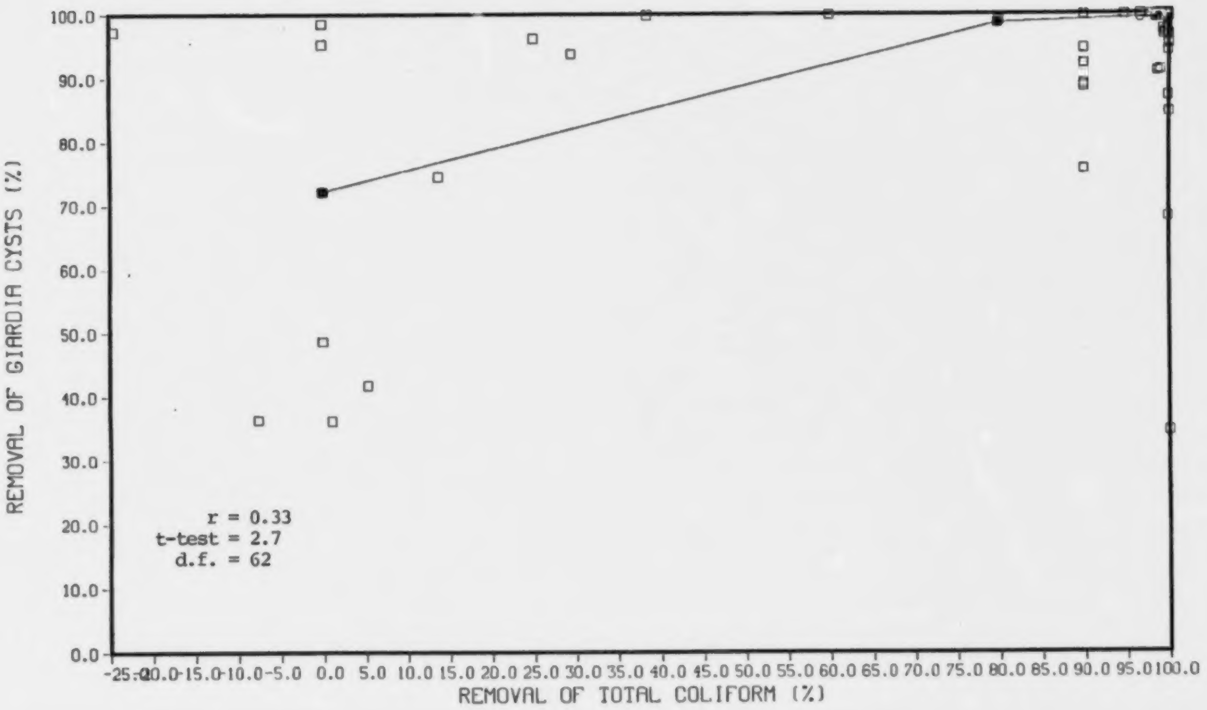


Figure G-13. Observations of percent removal of Giardia cysts with corresponding percent removal of total coliform bacteria. Data obtained from Table A-1 and Table A-2. The solid points show the median for each 8 points, conneccted by a line.

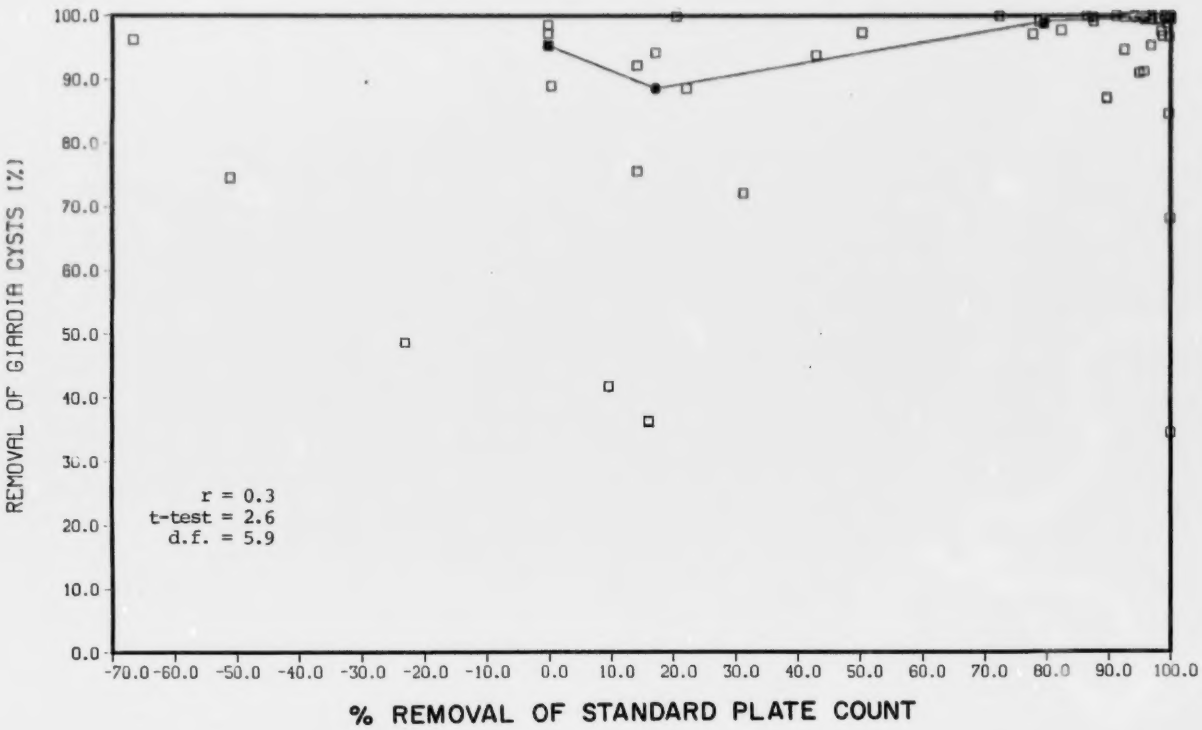


Figure G-14. Observations of percent removal of Giardia cysts with corresponding percent removal of standard plate count bacteria. Data obtained from Table A-1 and Table A-2. The solid points show the median for each 8 points connected by a line.

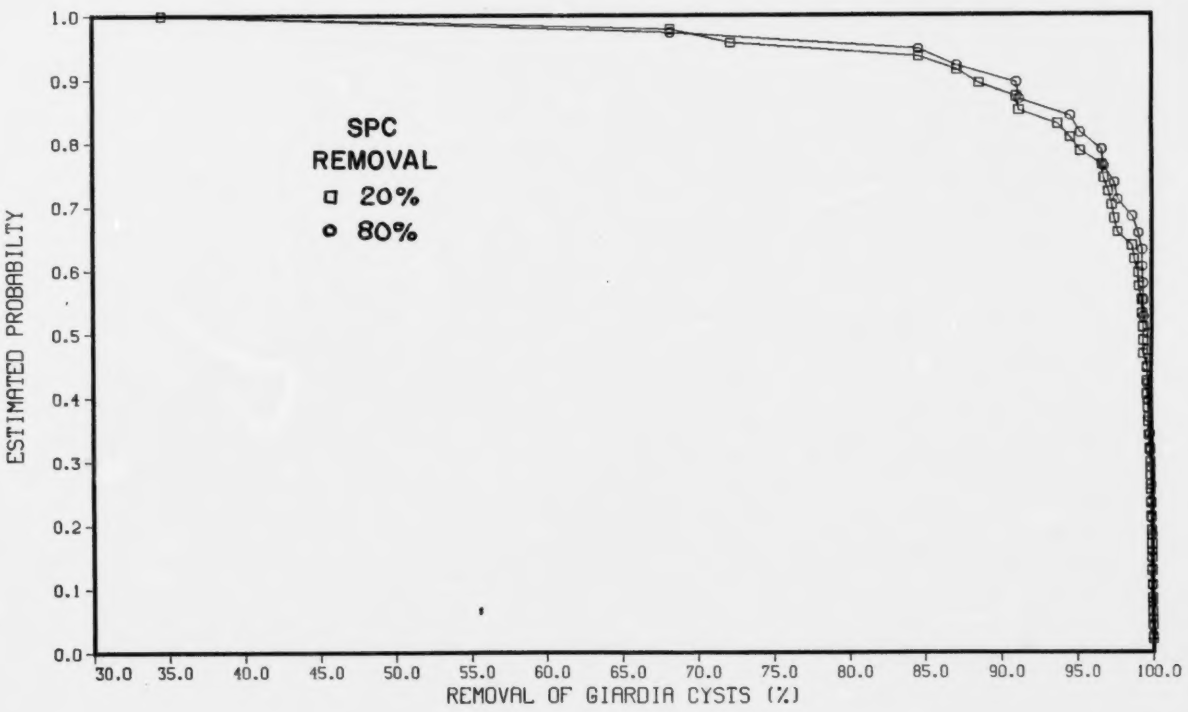


Figure G-15. Probability of a given percent removal of Giardia cysts for specific percent removal of standard plate count bacteria. Data from Table A-1 and plotted in Figure G-14.

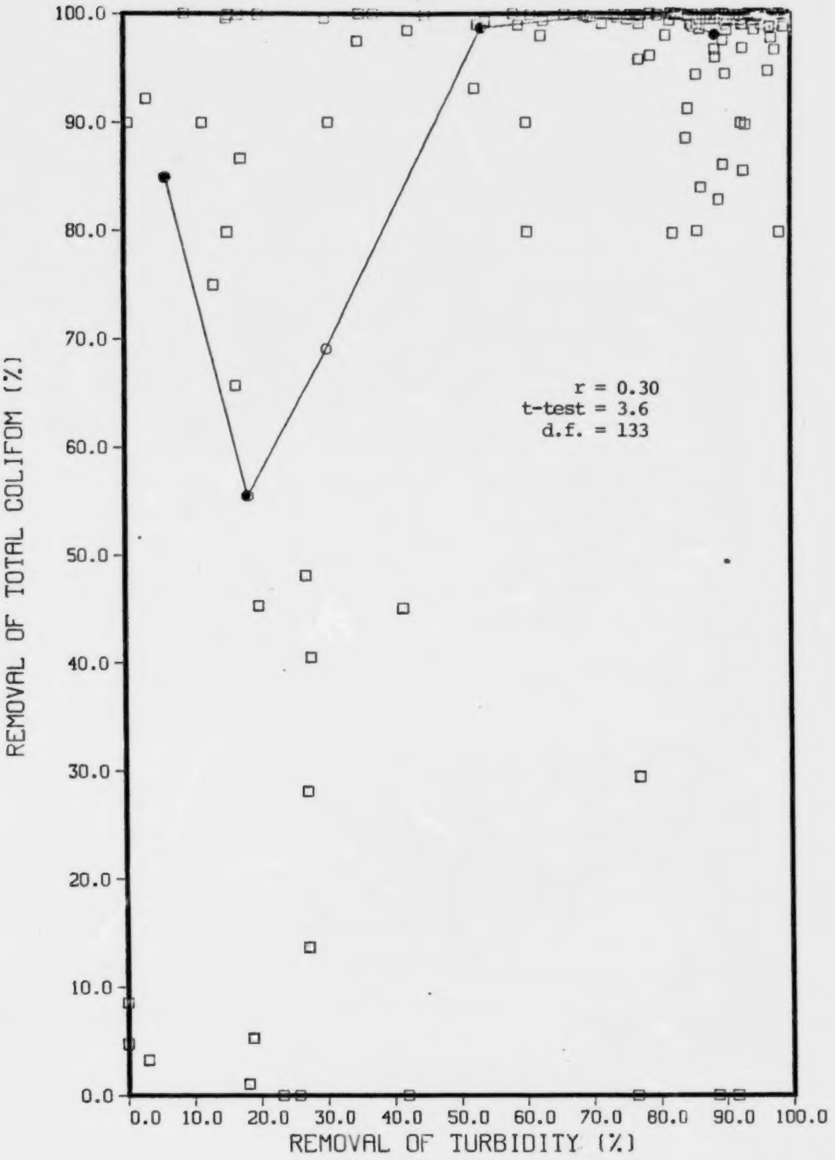


Figure G-16. Observation of percent removal of total coliform bacteria with corresponding percent removal of turbidity. Data obtained from Table A-1. The solid points show time median for each 10 points connected by a line.

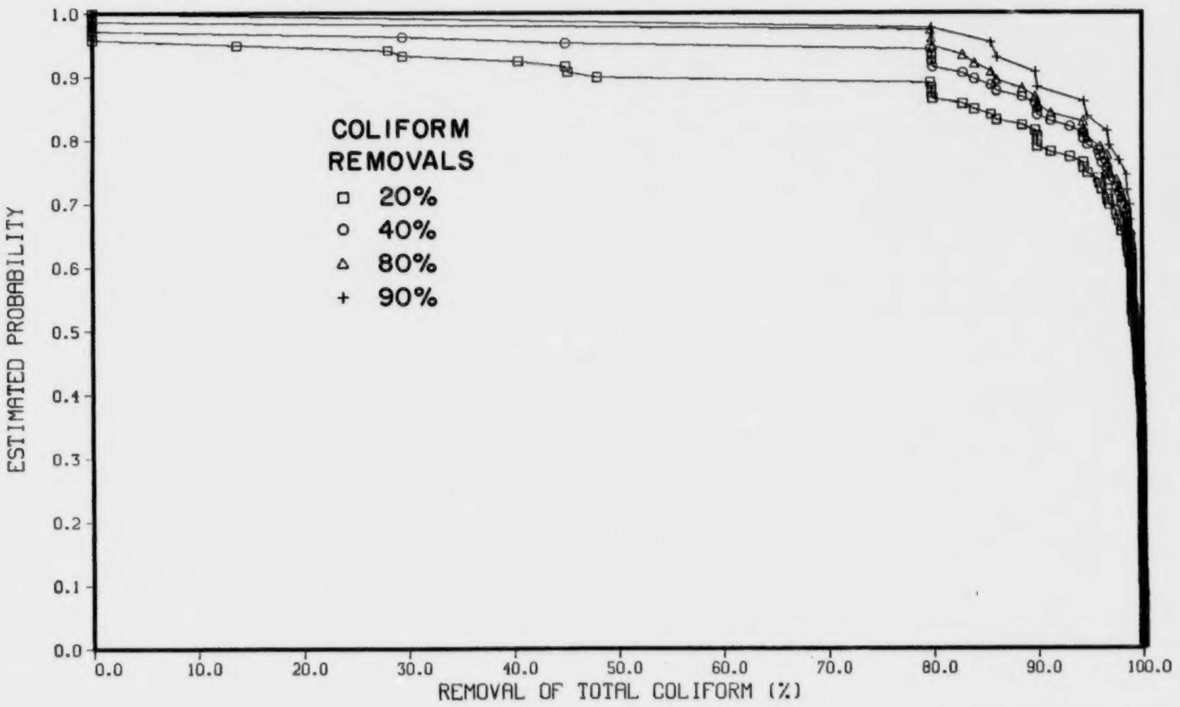


Figure G-17. Probability of a given percent removal of total coliform bacteria for specific percent removal of turbidity. Data from Table A-1 and plotted in Figure G-13.

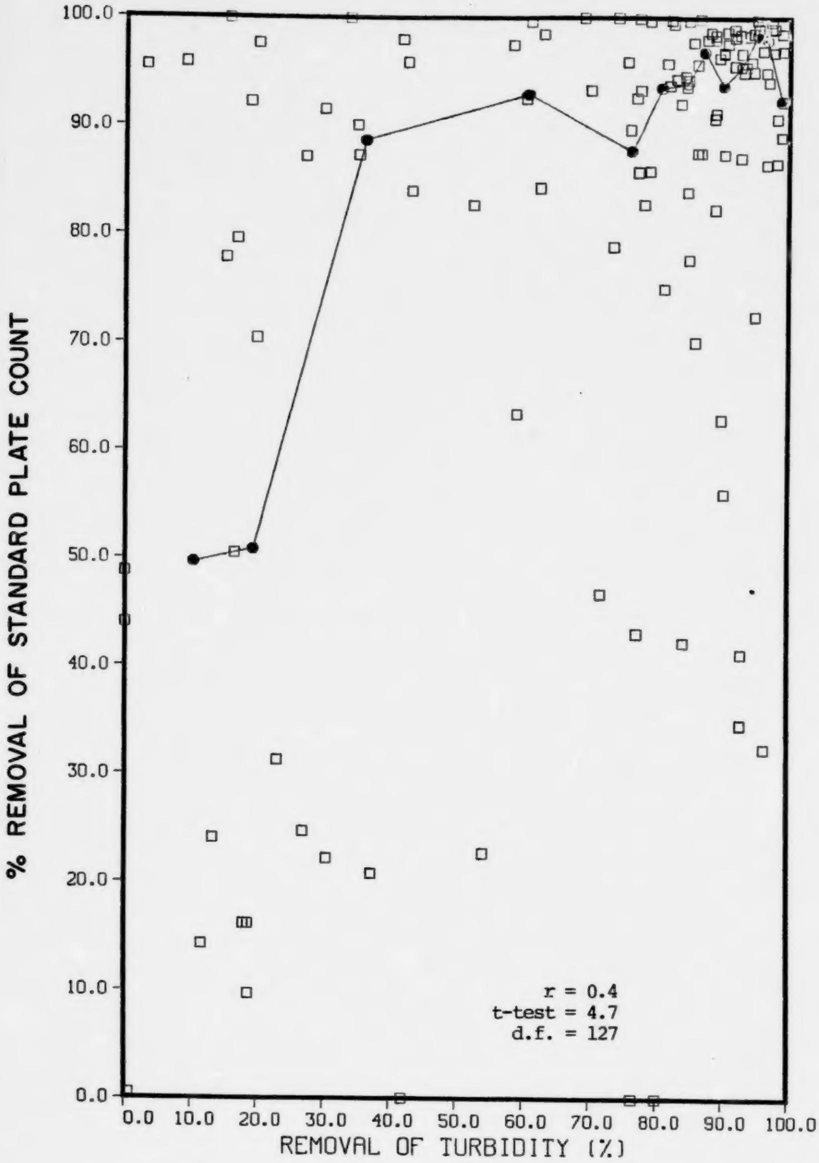


Figure G-18. Observations of percent removal of standard plate count with corresponding percent removal of turbidity. Data obtained from Table A-1. The solid points show the median for each 10 points connected by a line.

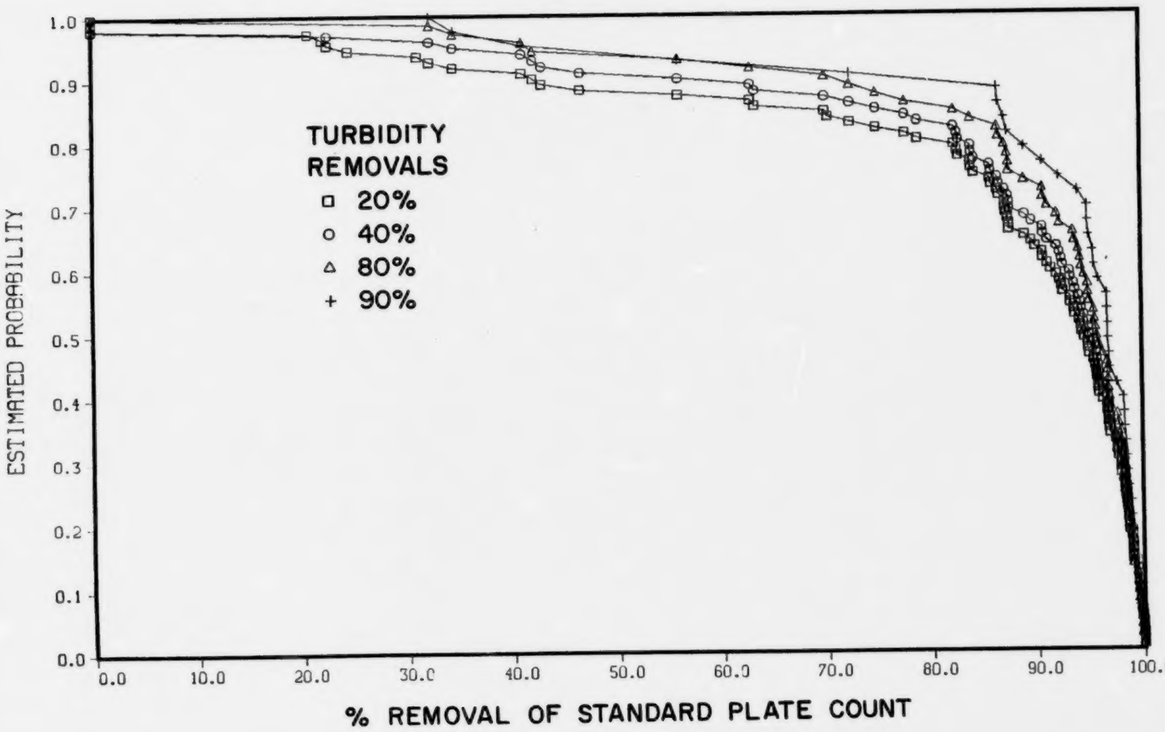


Figure G-19. Probability of a given percent removal of standard plate count for specific percent removal of turbidity. Data from Table A-1 and plotted in Figure G-18.

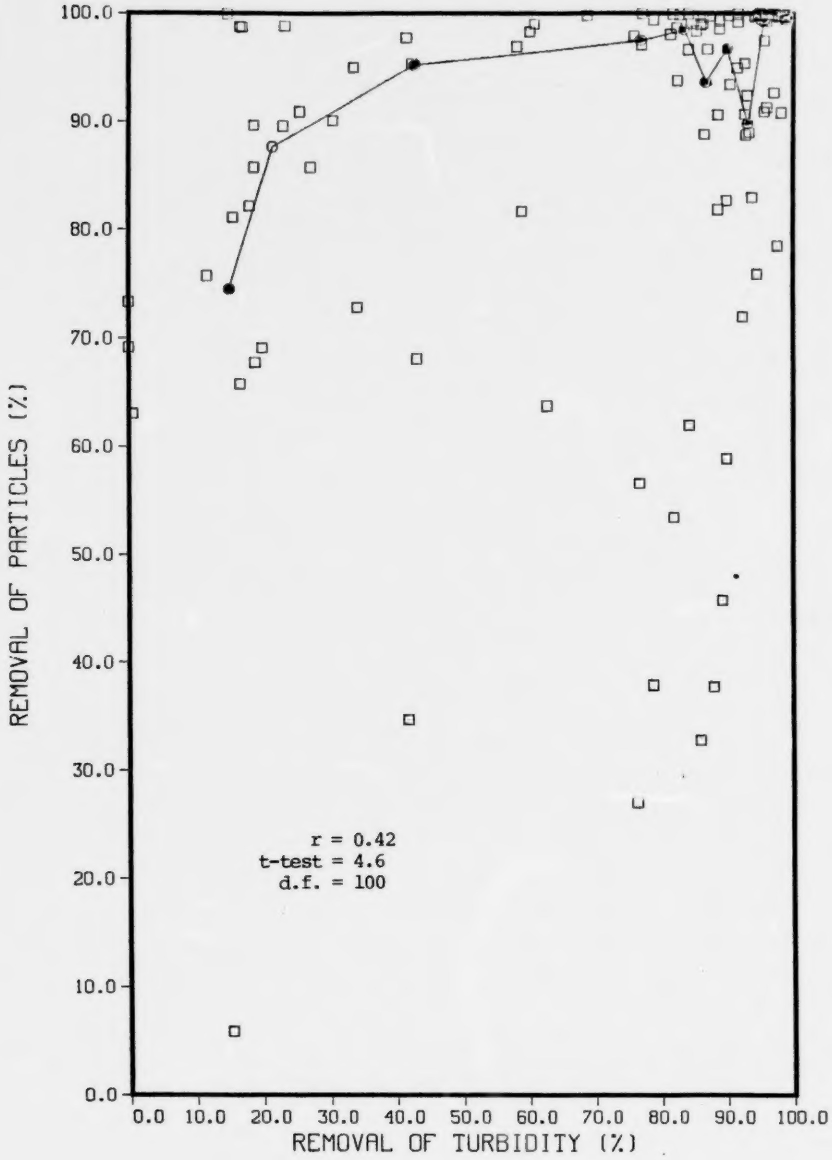


Figure G-20. Observations of percent removal of particles with corresponding percent removal of turbidity. Data were obtained from Table A-1. The solid points show the median for each 10 points connected by a line.

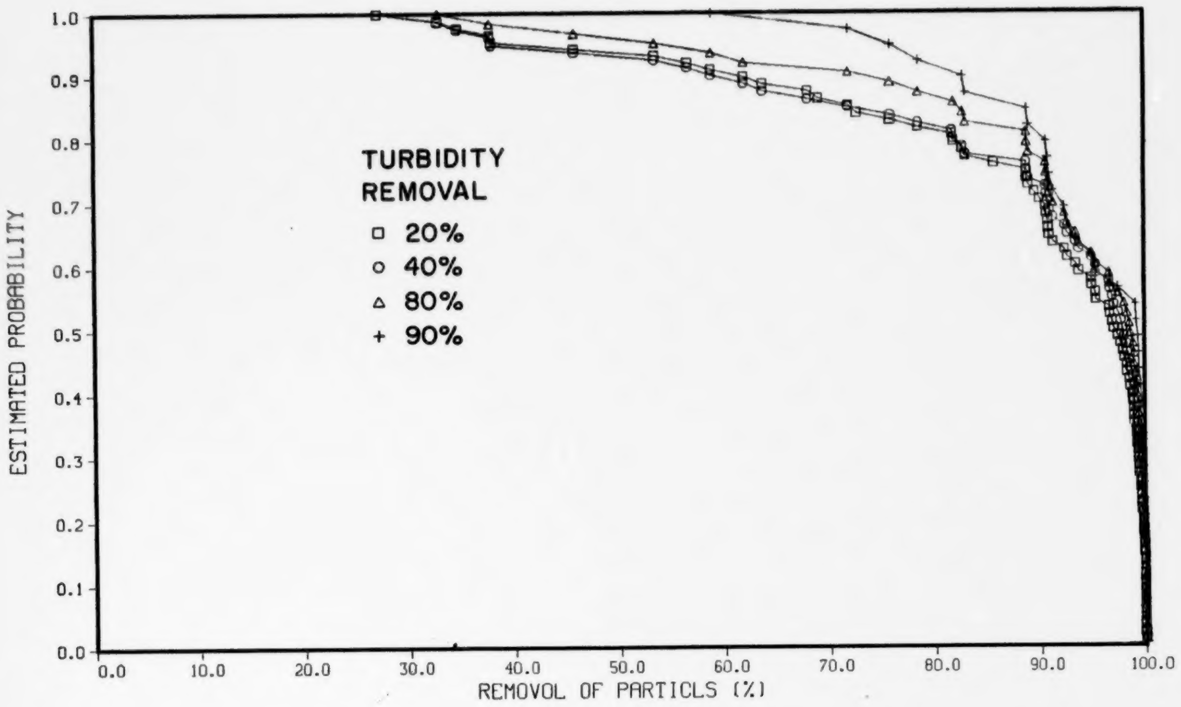


Figure G-21. Probability of a given percent removal of particles for specific percent removal of turbidity. Data from Table A-1 and plotted in Figure G-20.

APPENDIX H

RESULTS FROM FAMILIARIZATION TESTING, HORSETOOTH TESTING AND SPRING RUNOFF TESTING

FAMILIARIZATION TESTING

The first group of figures, Figures H-1 to H-12, show turbidity vs time relationships developed during a "familiarization" testing period. These curves show that within about one-hour the effluent turbidity was "stabilized", i.e. did not change significantly with time. From these results the run time of one-hour was used as an index time for sampling in subsequent testing. Horsetooth Reservoir water was used for this purpose. The purposes of the familiarization phase were to become familiar with the pilot plant, and to size and calibrate chemical feed tanks, pumps, etc. Some 22 test runs were completed during the familiarization phase. The testing was conducted during the period 11/9/82 to 2/9/83. The pilot plant was located on the floor of the Hydraulics Laboratory at the Engineering Research Center, which can withdraw water from the adjacent Horsetooth Reservoir.

HORSETOOTH TESTING

Sixty eight tests were performed using Horsetooth Reservoir water, exclusive of the familiarization testing. These 68 tests included 46 effluent turbidity vs chemical dose tests. From these data typical U-shaped curves were developed. Based on these curves, three categories of chemical dosages were designed: "zero" dose, "optimum" dose, and "nonoptimum" dose. These dose categories were used to evaluate the effectiveness of coagulant dosage on removal of *Giardia* cysts and coliform bacteria. The results are summarized in Table H-1. Figures H-13 to Figure H-16 show the effectiveness of different chemicals on turbidity removal. Figures H-17, H-18, H-19 show various associations between parameters, while Figures H-20 and H-21 show the effect of run time on parameters.

SPRING RUNOFF TESTING

When the 1983 spring runoff started the WATER BOY was located at Fort Collins Water Treatment Plant No. 1 on the Cache La Poudre River. Turbidity levels at this time ranged from 12 to 44 NTU. The results illustrate the contrust in treating high turbidity water compared with low turbidity water, the focus of the research.

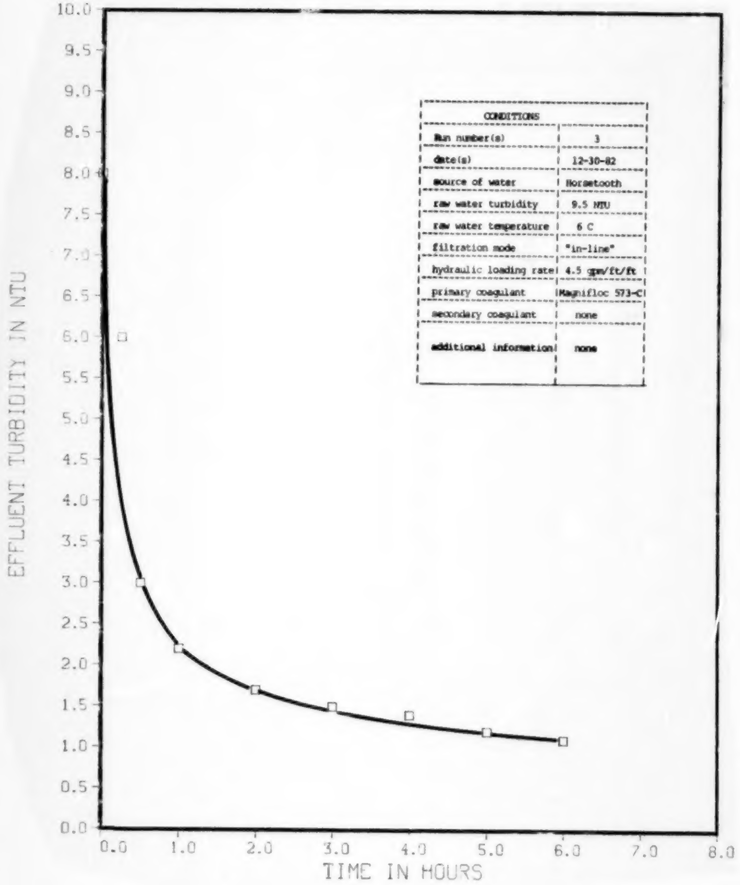


Figure H-1. Effluent-turbidity vs time using 0.5 mg/L of Magnifloc 573-C. Familiarization testing.

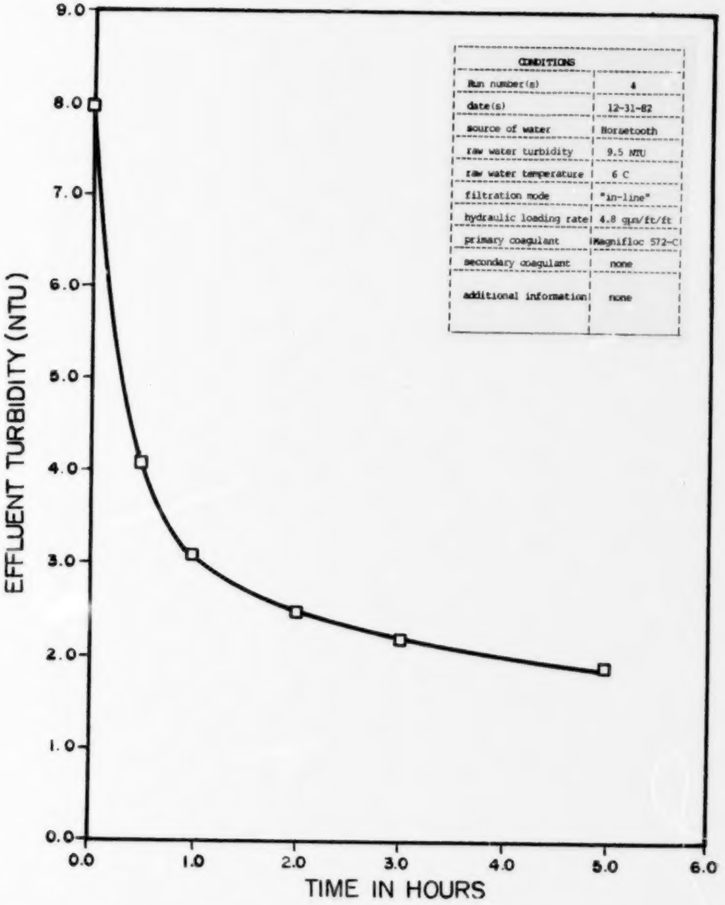


Figure H-2. Effluent-turbidity vs time using 0.5 mg/L of Magnifloc 572-C. Familiarization testing.

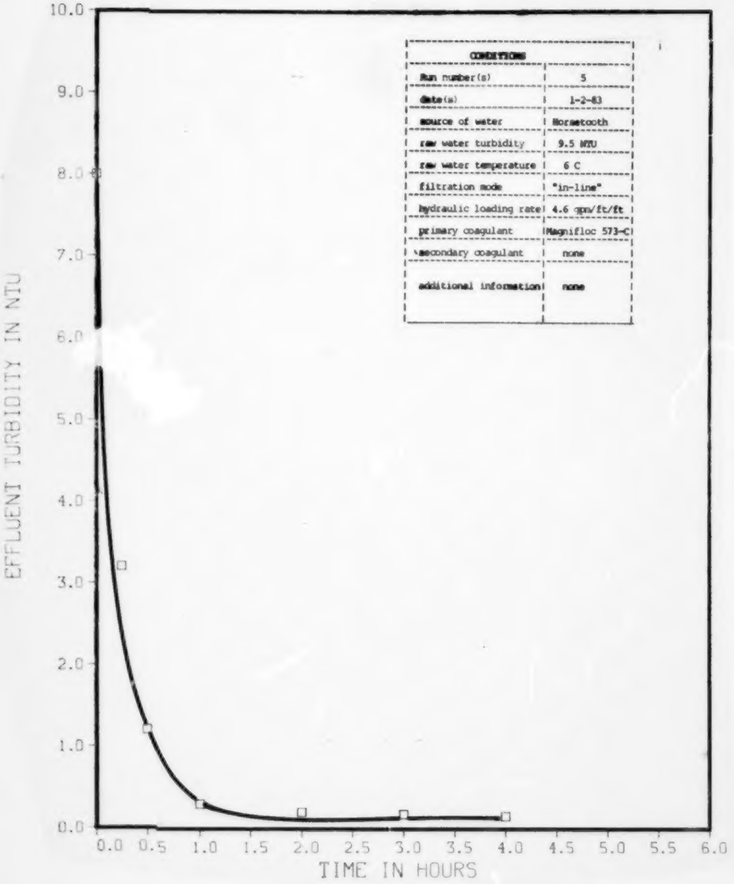


Figure H-3. Effluent-turbidity vs time using 1.5 mg/L of Magnifloc 573-C. Familiarization testing.

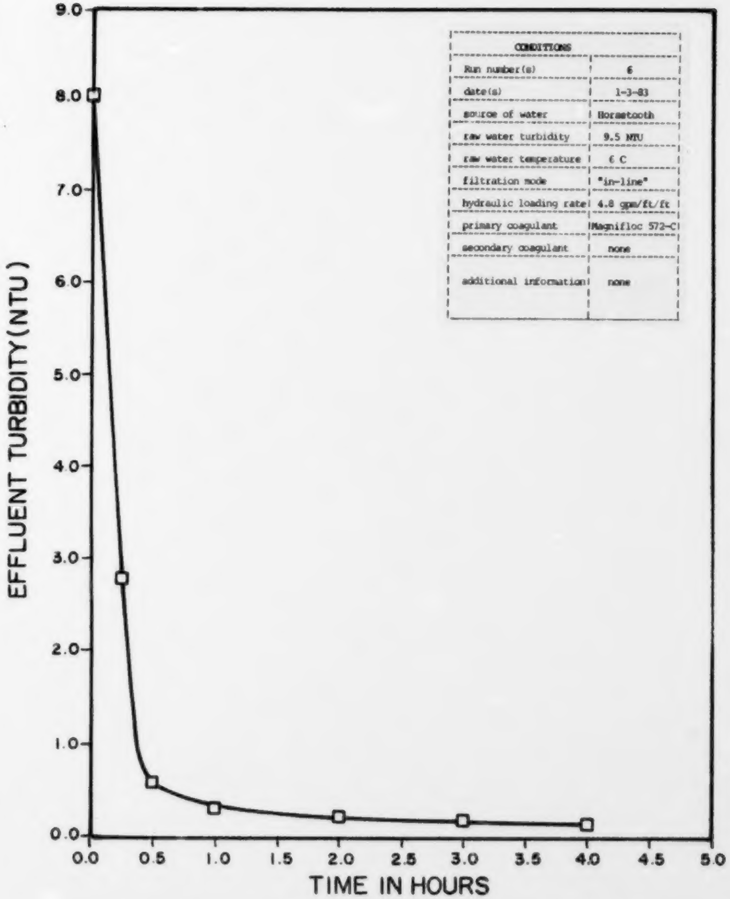
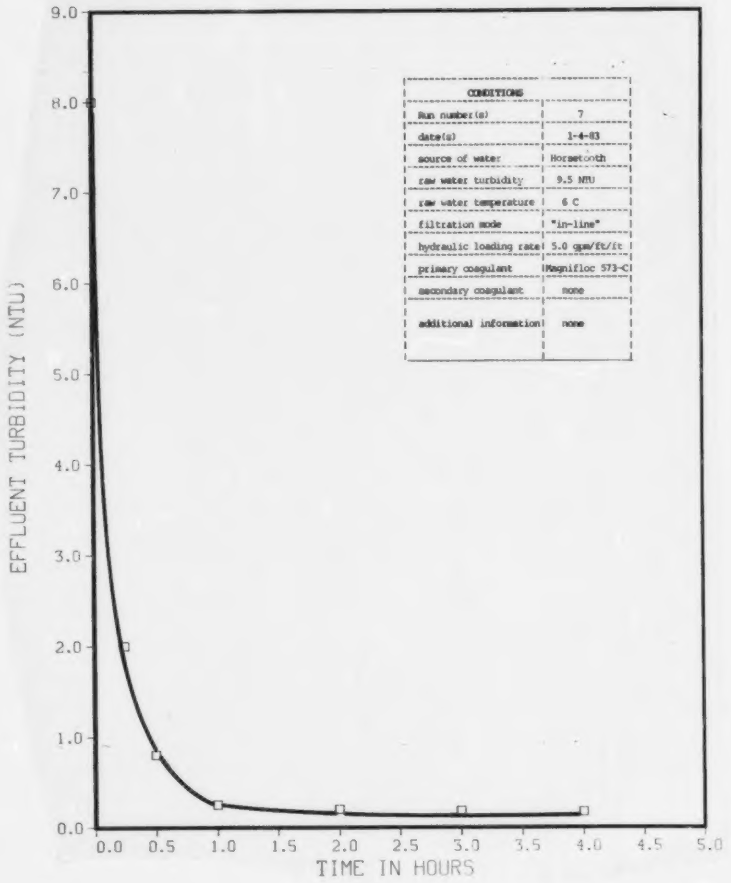
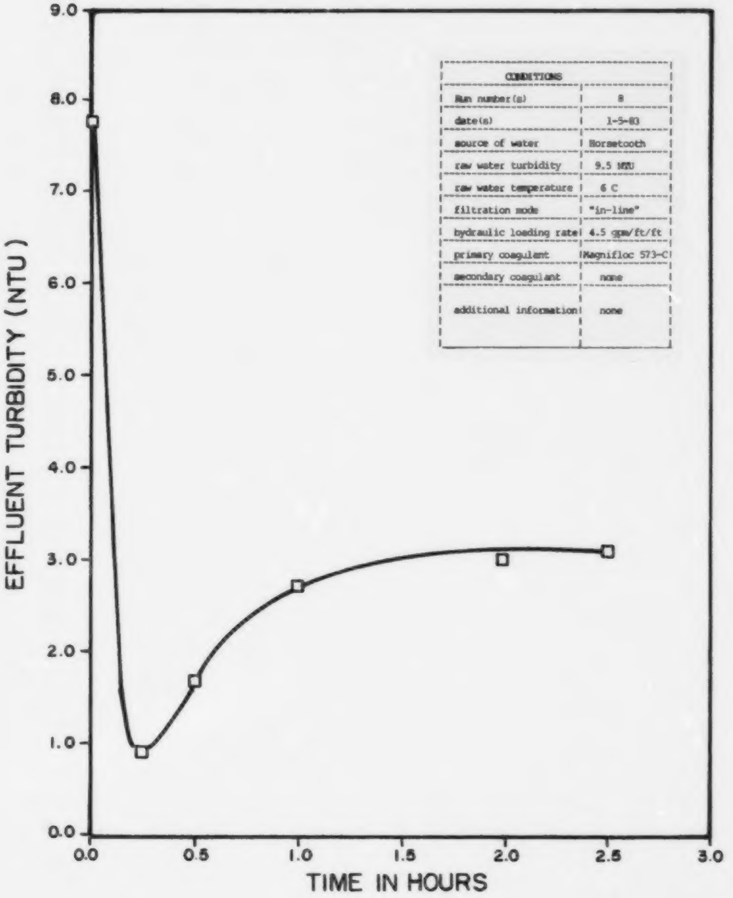


Figure H-4. Effluent-turbidity vs time using 1.5 mg/L of Magnifloc 572-C. Familiarization testing.



CONDITIONS	
Run number(s)	7
date(s)	1-4-83
source of water	Horsetooth
raw water turbidity	9.5 NTU
raw water temperature	6 C
filtration mode	"in-line"
hydraulic loading rate	5.0 gpm/ft/ft
primary coagulant	Magnifloc 573-C
secondary coagulant	none
additional information	none

Figure H-5. Effluent-turbidity vs time using 3.8 mg/L of Magnifloc 573-C. Familiarization testing.



CONDITIONS	
Run number(s)	8
date(s)	1-5-83
source of water	Horsetooth
raw water turbidity	9.5 NTU
raw water temperature	6 C
filtration mode	"in-line"
hydraulic loading rate	4.5 gpm/ft/ft
primary coagulant	Magnifloc 573-C
secondary coagulant	none
additional information	none

Figure H-6. Effluent-turbidity vs time using 3.8 mg/L of Magnifloc 573-C. Familiarization testing.

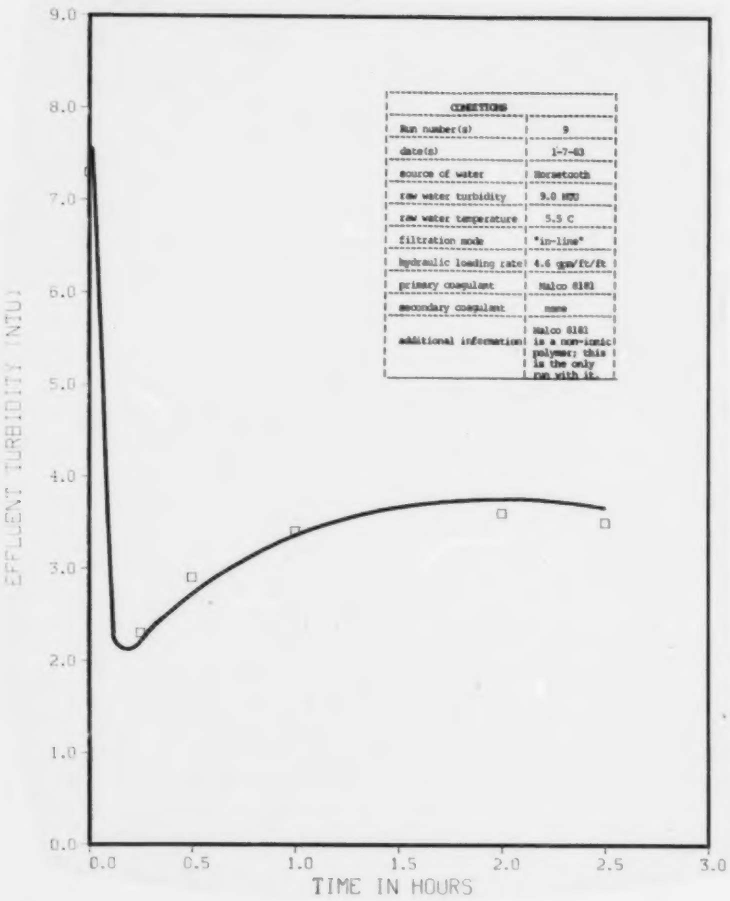


Figure H-7. Effluent-turbidity vs time using 6.7 mg/L of Nalco 8181 (non-ionic polymer). Familiarization testing.

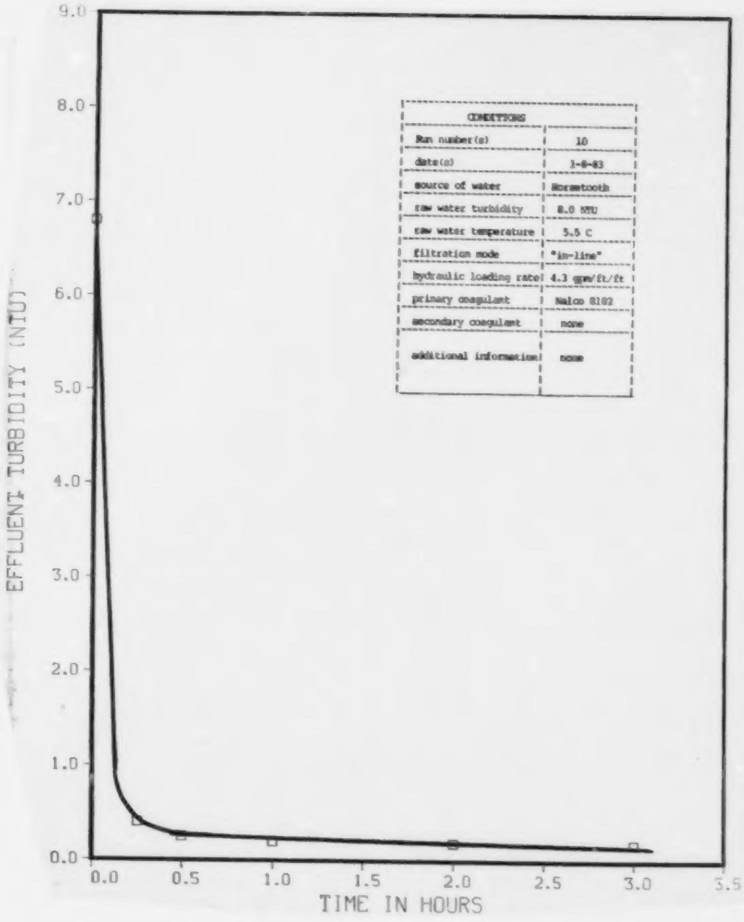


Figure H-8. Effluent-turbidity vs time using 4.3 mg/L of Nalco 8102. Familiarization testing.

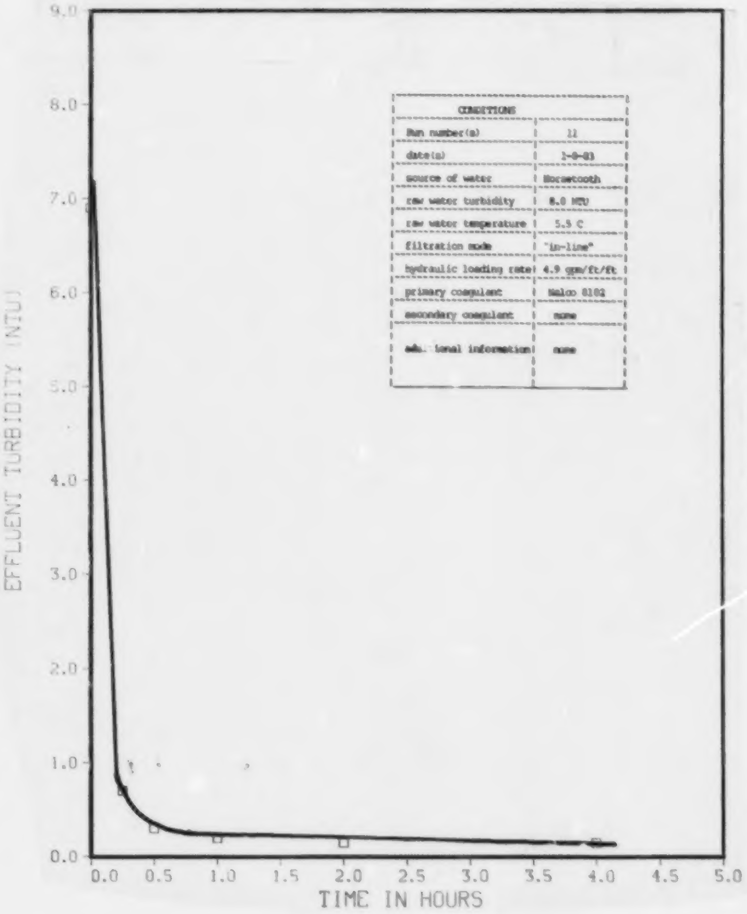


Figure H-9. Effluent-turbidity vs time using 8.0 mg/L of Nalco 8102. Familiarization testing.

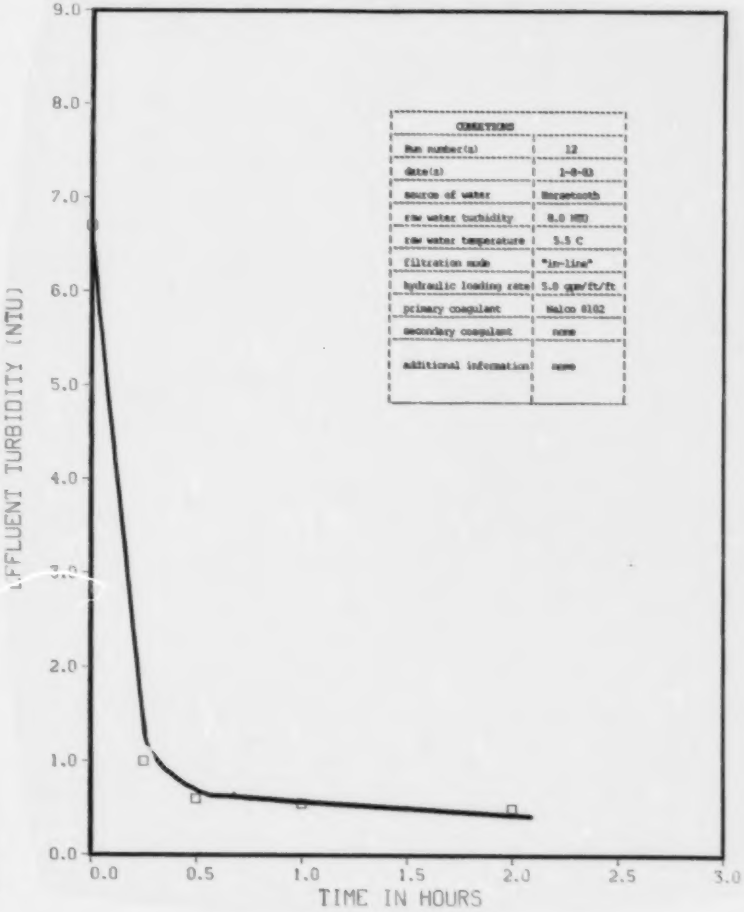


Figure H-10. Effluent-turbidity vs time using 10.5 mg/L of Nalco 8102. Familiarization testing.

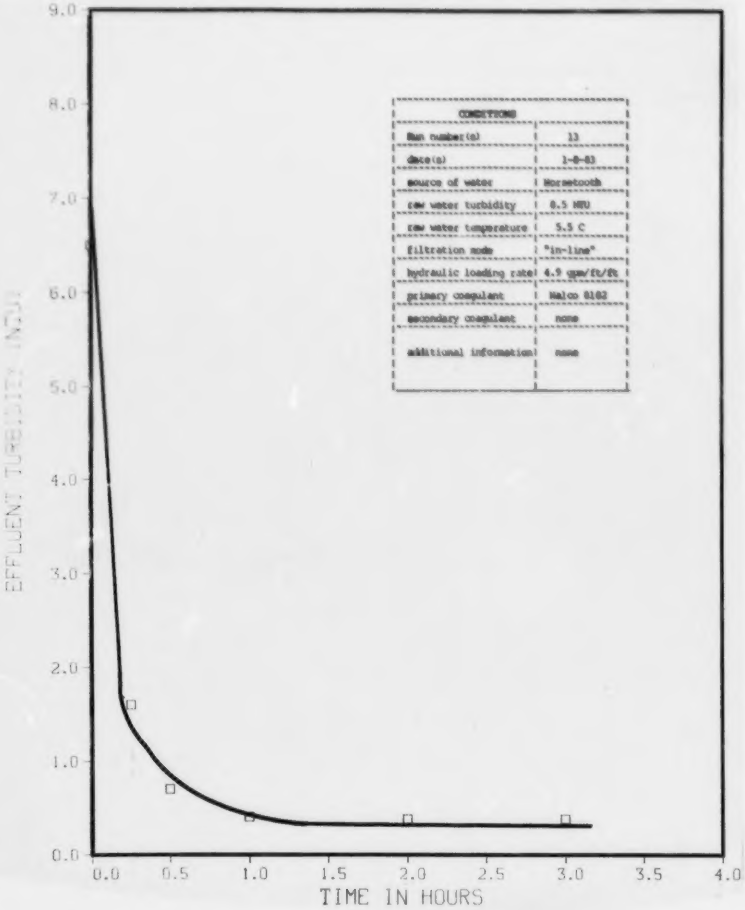


Figure H-11. Effluent-turbidity vs time using 0.9 mg/L of Nalco 8101. Familiarization testing.

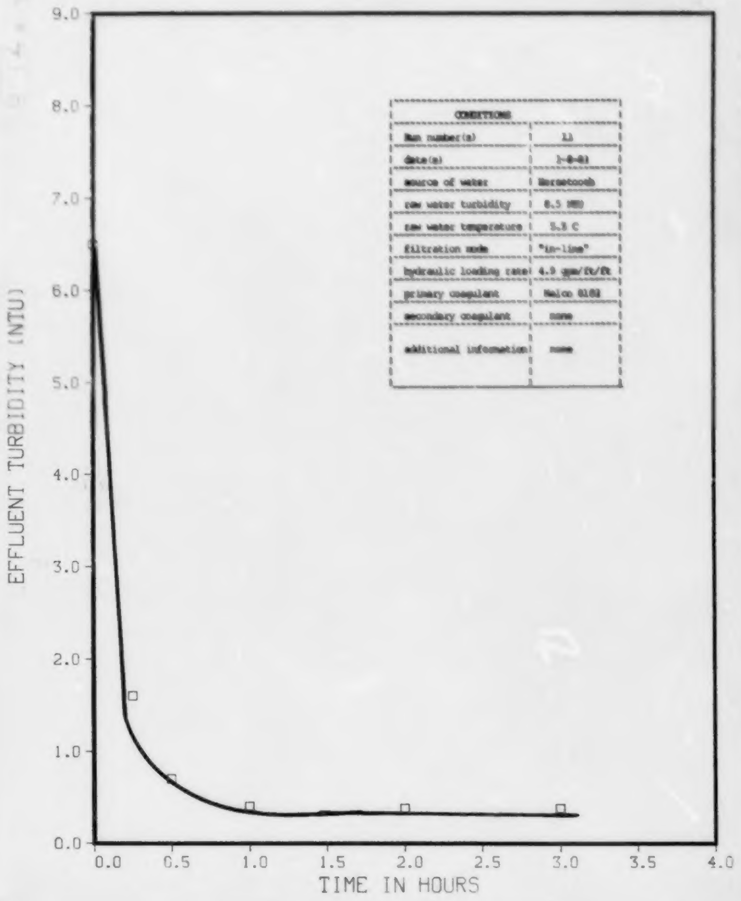


Figure H-12. Effluent-turbidity vs time using 6.7 mg/L of Magnifloc 572-C. Familiarization testing.

Table H-1. Effect of coagulant dosages on removals of coliform bacteria and *Giardia* cysts for Horsetooth water.1/11/

Run #	Coagulant Dosage Category2/3/	Coagulant Used		Percent Removals10/		
		Chemical Species6/	Chemical Dosage5/ (mg/L)	Turbidity	Coliforms8/12/	*Giardia* Cysts4/7/13/
50	None	None	0	+	*	>99
57	None	None	0	14	*	<1
60	None	None	0	14	*	84
61	None	None	0	11	*	<1
62	None	None	0	13	*	<1
74	None	None	0	9	33	**
99	None	None	0	3	27	41
49	optimum	573-C	2.5	93	*	>99
52	optimum	8102	2.5	+	95	>99
58	optimum	8102	5.5	94	*	>99
73	optimum	572-C	2.5	93	97	**
76	optimum	alum	25	97	96	**
90	optimum	8102	4.0	94	>99	>99
92	optimum	alum	12	76	98	97
98	optimum	alum	15	84	98	94
105	optimum	alum/8102	15/4	89	98	93
106	optimum	alum/8102	15/4	90	96	>99
51	nonoptimum	573-C	8.0	+	>99	>99
59	nonoptimum	8102	11.0	86	98	>99
75	nonoptimum	572-C	1.0	76	81	**
91	nonoptimum	8102	1.0	83	96	>99

1/ Abstracted from Table B-1

2/ Three dosage categories are: i) no coagulants used, indicated as "none"; ii) "optimum" coagulant dosage is with respect to turbidity removal; iii) "nonoptimum" coagulant dosage is a dosage greater than or less than "optimum."

3/ "Optimum" and "nonoptimum" are dosages based on Figures 3-1 to 3-4

4/ Based on detected influent cyst concentration

5/ Alum dose reported is mg/L as $Al_2(SO_4)_3 \cdot 14H_2O$

6/ Nalco 8102, Magnifloc 572-C, Magnifloc 573-C

7/ Double asterisk indicates cysts used were of questionable viability

8/ Asterisk indicates no data; missed dilution range

9/ No effluent turbidity sample taken obtained

10/ Data represents removals after one hour of filtration

11/ Influent turbidity levels were 7.0 NTU for all tests and water temperatures ranged between 10 and 12°C

12/ Influent coliform concentrations ranged from 220/100 ml to 30000/100 mL; median was 8700/100 mL.

13/ Influent detected *Giardia* cyst concentrations ranged between 10/L to 2000/L; median was 110/L.

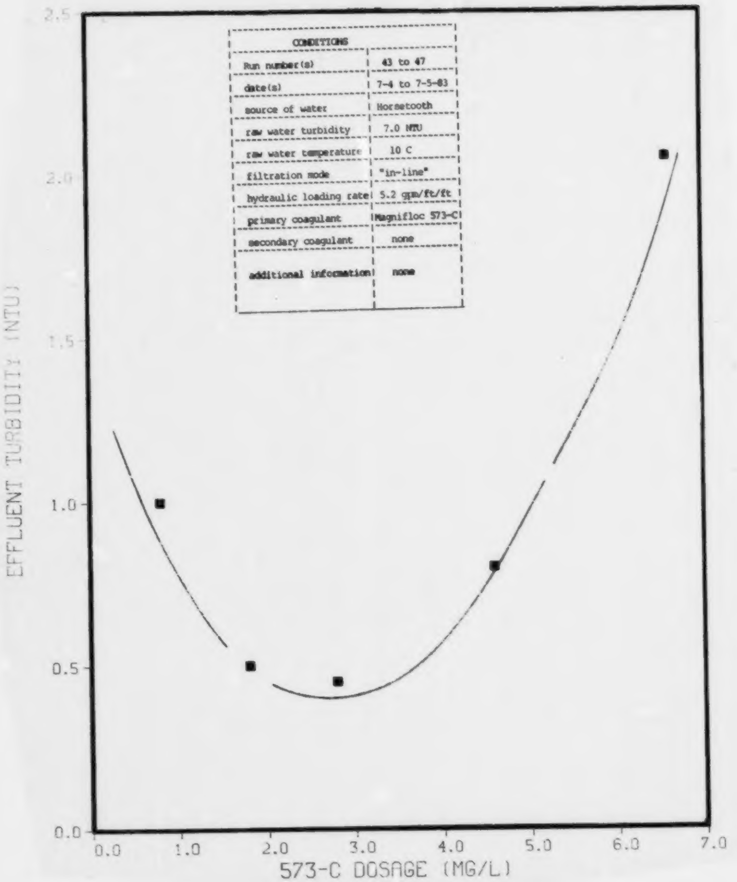


Figure H-13. Effluent turbidity vs dose of Magnifloc 573-C. Horsetooth water.

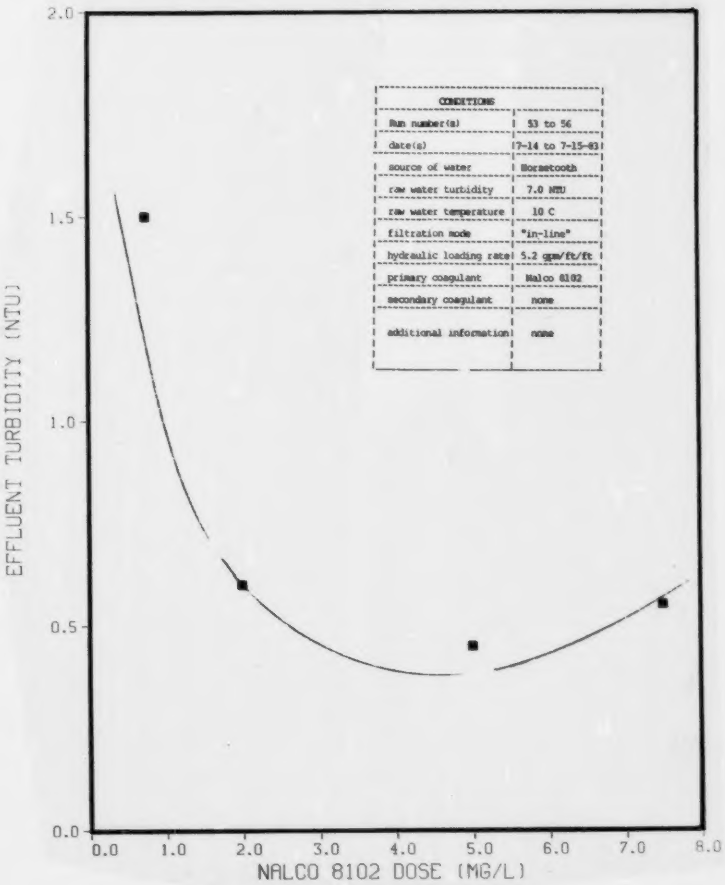


Figure H-14. Effluent turbidity vs dose of Nalco 8102. Horsetooth water.

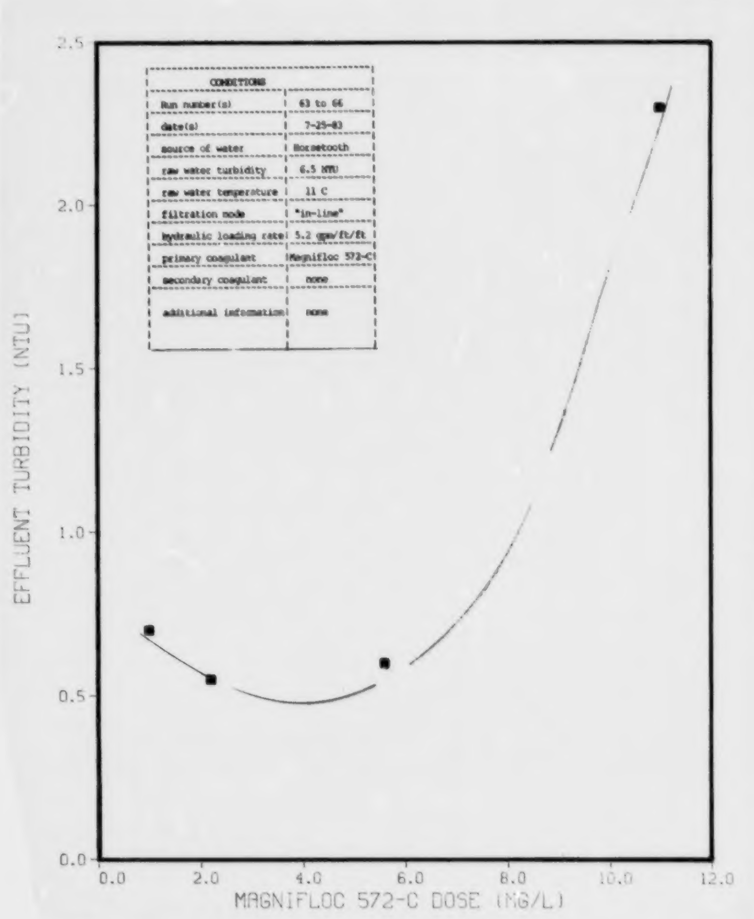


Figure H-15. Effluent turbidity vs dose of Magnifloc 572-C. Horsetooth water.

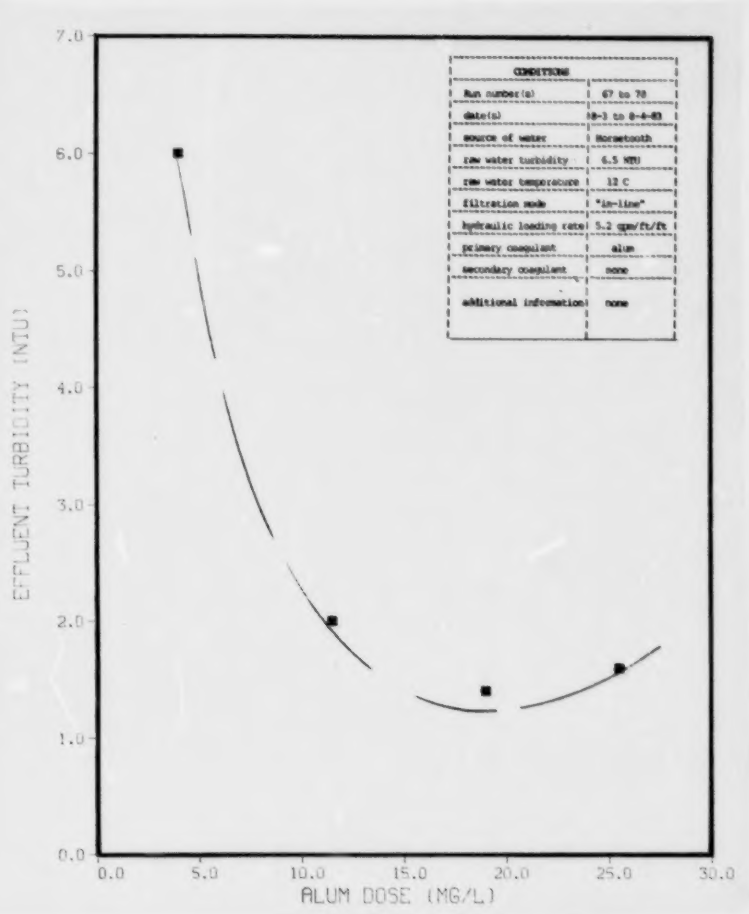


Figure H-16. Effluent turbidity vs dose of alum as $Al_2(SO_4)_3\ 14H_2O$. Horsetooth water.

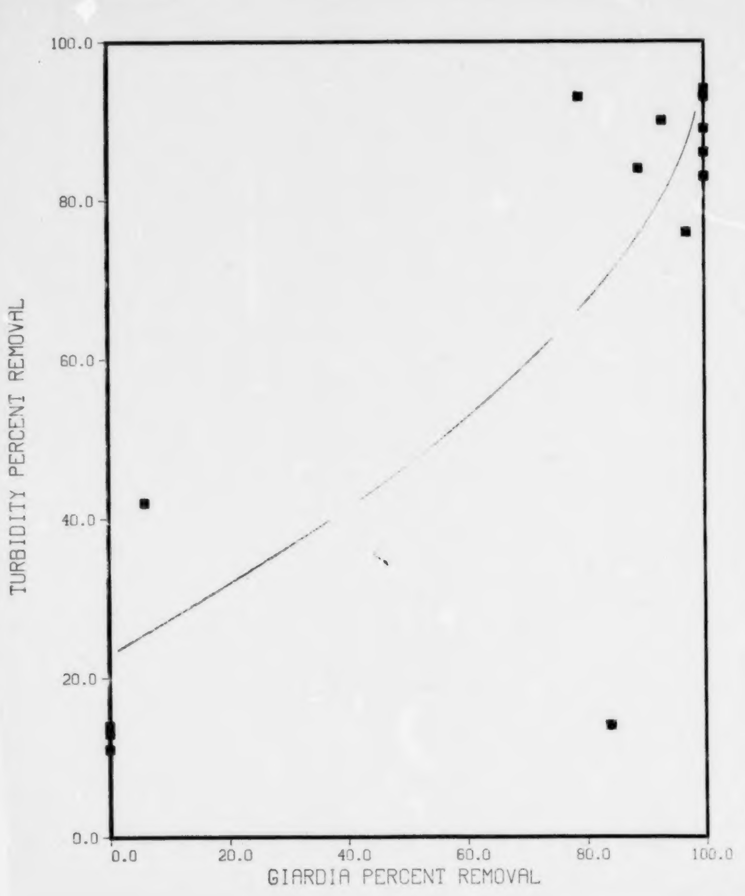


Figure H-17. Percent removal of turbidity vs percent removal of Giardia cysts. Horsetooth water. Raw water characteristics were 7.0 NTU and temperature 10-12°C.

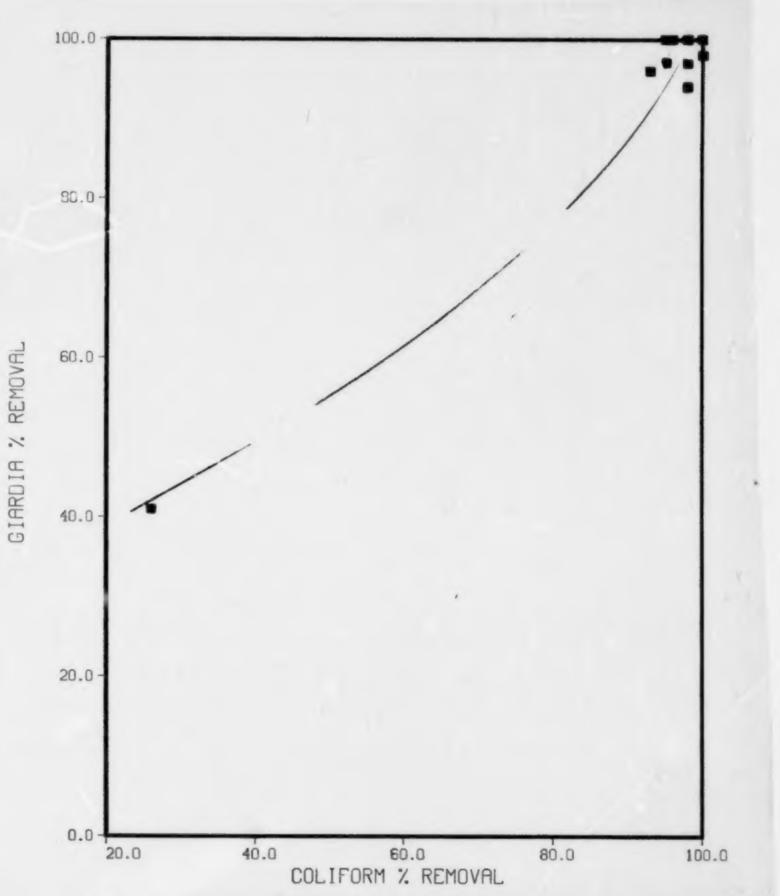


Figure H-18. Percent removal of coliform bacteria vs percent removal of Giardia cysts. Horsetooth water. Raw water characteristics were 7.0 NTU and 10-12°C.

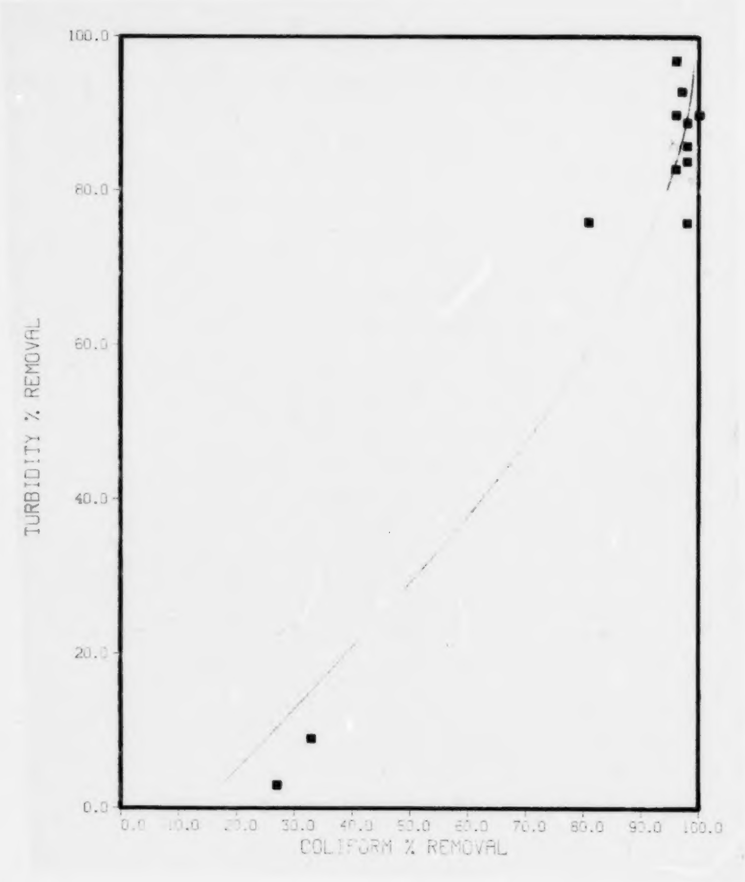


Figure H-19. Percent removal of turbidity vs percent removal of coliform bacteria. Horsetooth water. Raw water characteristics were 7.0 NTU and 10-12°C.

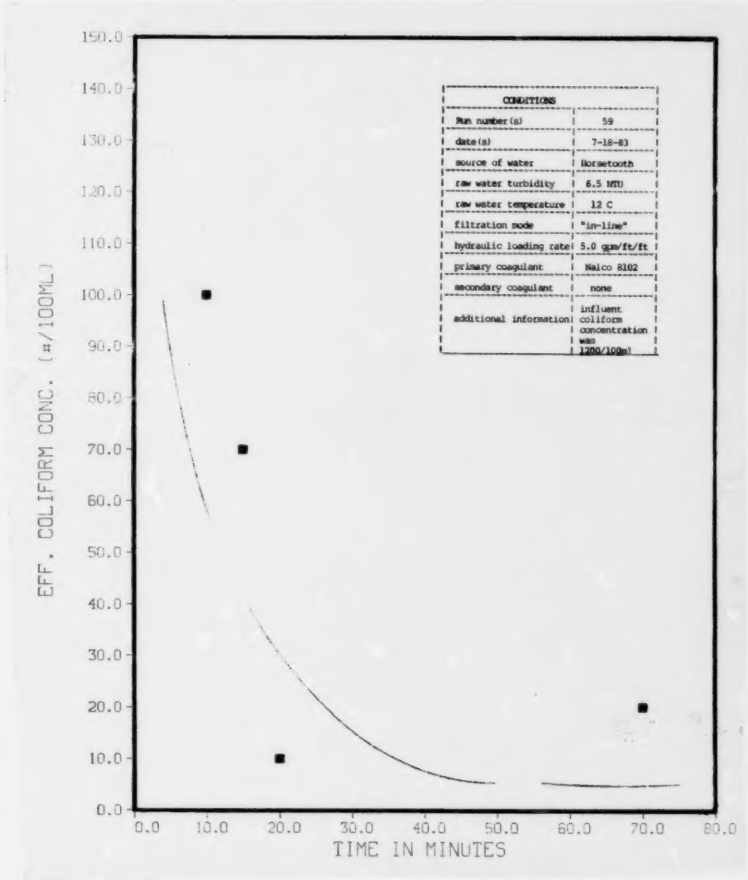


Figure H-20. Effluent coliform bacteria concentrations vs time. Horsetooth water.

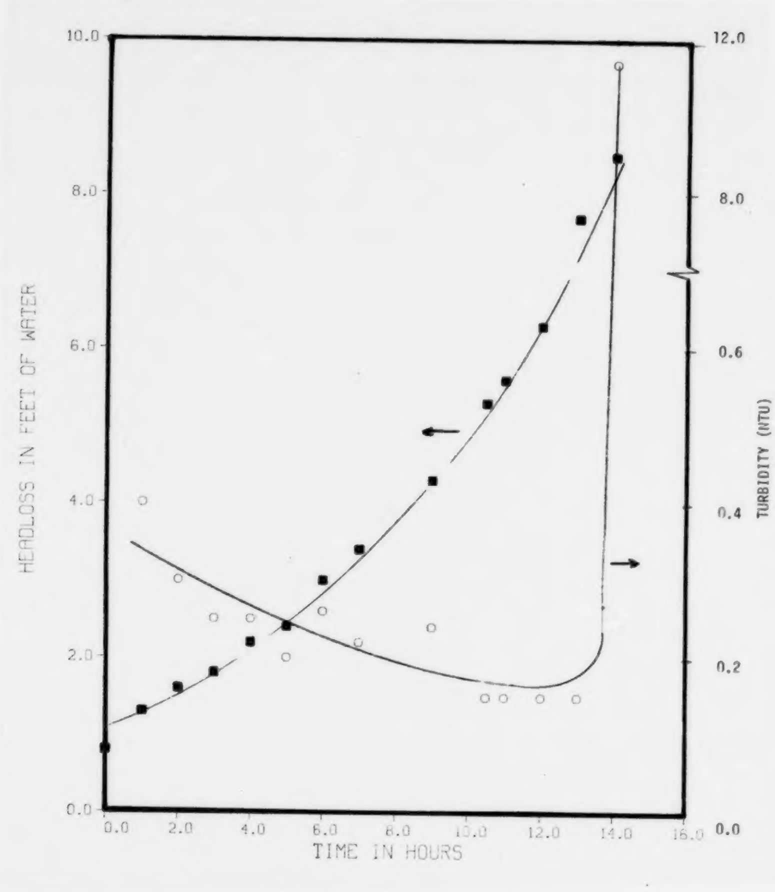


Figure H-21. Headloss and effluent turbidity vs time for Run 78. Raw water was 7.0 NTU, and 6 °C. Nalco 8102 dose used was 3.5 mg/L.

Spring Runoff Testing

The spring runoff testing was conducted from 4/23/83 to 6/1/83 at the Fort Collins Water Treatment Plant No. 1. The water used for testing was from the Cache La Poudre River during spring runoff. The intent was to begin testing in early March to experiment with low turbidity, i.e. less than 1 NTU, raw water. Disruption of electric power, however, required replacement of a buried cable. This delayed the start up of the WATER BOY and the testing did not begin until after the start of the spring runoff in late April. So, when the spring runoff began, it was decided to go ahead and treat the high turbidity water. Table H-2 summarizes results, and Figures H-22 to H-27 provide results in graphical form.

During spring runoff, the raw water turbidities of the Cache La Poudre River ranged between 12 and 44 NTU, and raw water temperatures ranged between 7 and 10°C. The river's properties were continually changing, raw water turbidity fluctuations were as much as 10 NTU per hour.

Horsetooth Testing

The Horsetooth Reservoir testing was conducted from 7/3/83 to 8/31/83 at the Engineering Research Center at Colorado State University using Horsetooth Reservoir water as a raw water source. During the first part of this phase, the contaminant injection and sampling system was incorporated into the flow scheme of the WATER BOY, and tests were run to establish procedures for tests to determine removals of Giardia cysts and coliform bacteria. Once the protocol for Giardia cysts and coliform bacteria removals vs coagulant dose tests was established, 22 of these tests were conducted with Horsetooth water.

Although the focus of this research was to determine removals using raw waters with turbidities lss than 1 NTU, the Horsetooth Reservoir testing validated testing procedures, and provided results to compare those obtained from low turbidity testing. Horsetooth Reservoir provided a raw water source with predictable and relatively constant properties. The turbidity and temperature ranges for Horsetooth Reservoir water are 3 to 12 NTU and 2 to 15°C, respectively, over the annual cycle.

Horsetooth Reservoir water has low turbidity when compared to water sources which have turbidities as high as 100 to 200 NTU. But if compared to the water of the Cache La Poudre River during late fall and winter, Horsetooth Reservoir water is within a "medium" range of turbidity.

The traditional filtration practice is comprised of: i) particle destabilization by coagulation, ii) floc production, and iii) floc penetration into the filter. This practice is applicable to Horsetooth Reservoir water. But when the raw water turbidity is below 1 NTU, this traditional practice of filtration does not seem to work. So, since Horsetooth Reservoir water could be properly coagulated and filtered in accordance with traditional practice, the use of this water source enabled

Table H-2. Spring Runoff Results[1/][3/]

Run No.	Coagulant Dosage Category[2/]	Dose of Magnifloc 572-C mg/L	Turbidity (NTU)		
			Influent	Effluent[4/]	Percent Removal
34	none	0	23	10	57
36	none	0	35	11	69
25	optimum	8.5	27	1.0	96
27b	optimum	9.0	30	1.5	95
28a	optimum	17.0	30	1.5	95
29	optimum	10.5	44	2.0	95
30	optimum	8.0	44	1.5	97
33	optimum	6.5	23	1.0	96
35	optimum	9.0	34	1.5	96
37	optimum	12.5	35	1.3	96
38	optimum	7.0	16	1.1	93
23	nonoptimum	1.5	27	15	44
24	nonoptimum	4.0	27	8.5	69
26	nonoptimum	30	27	3.0	89
27a	nonoptimum	4.0	27	3.0	89
28b	nonoptimum	35	30	6.5	78
31	nonoptimum	5.0	44	2.5	94
32	nonoptimum	21	35	3.0	91

[1/] Abstracted from Table B-1

[2/] Based upon results in Figure H-22

[3/] No Giardia cysts or coliform bacteria were injected during the spring runoff testing phase

[4/] Effluent turbidity after 60 minutes of operation

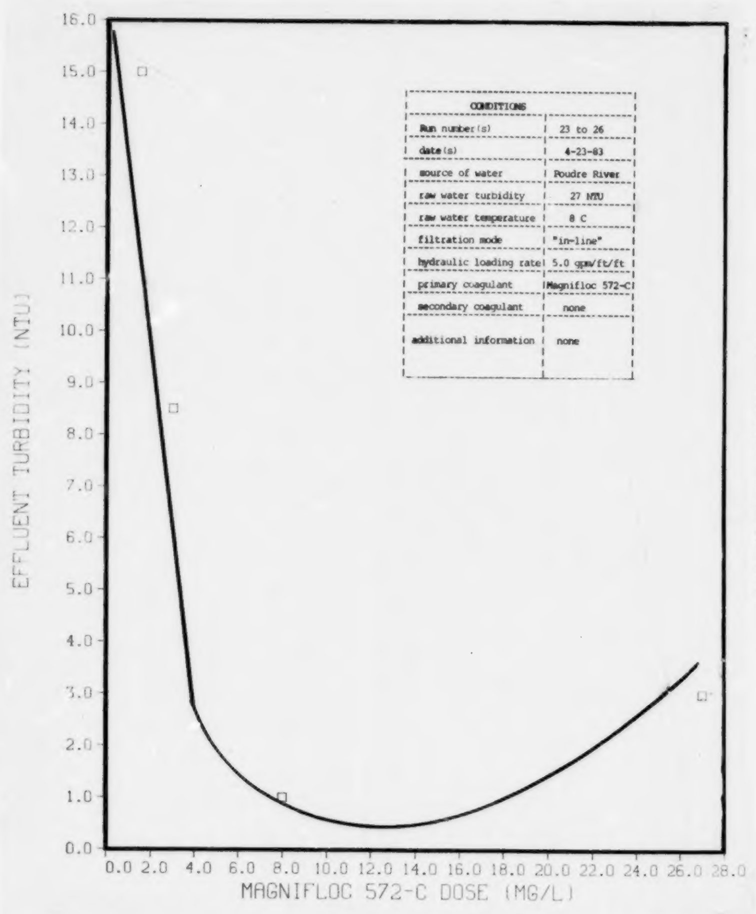


Figure H-22. Effluent turbidity vs Magnifloc 572-C dose. Horsetooth water.

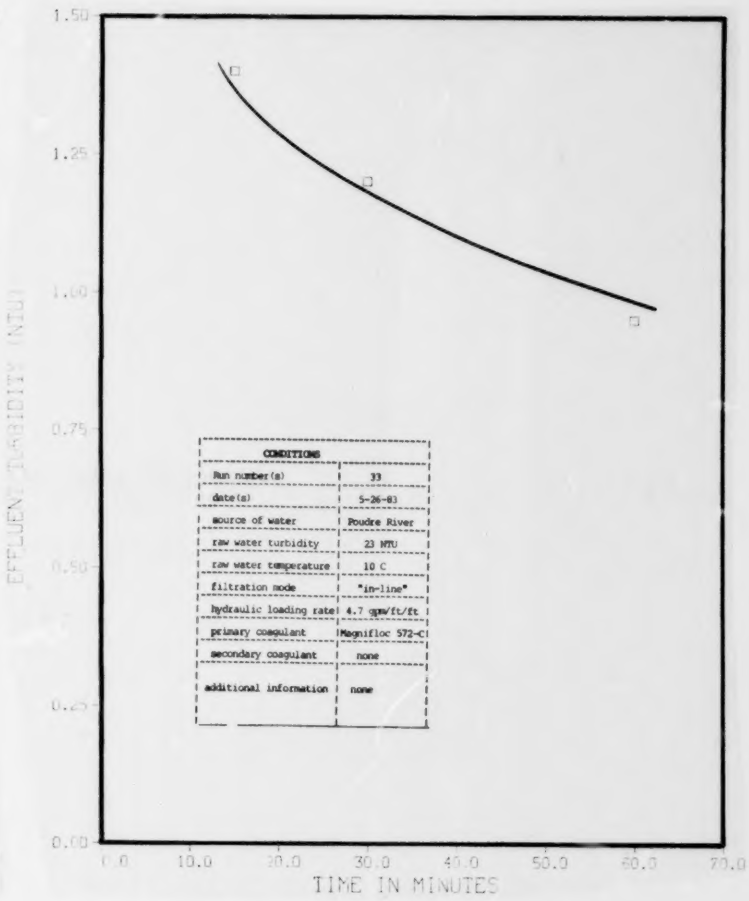


Figure H-23. Effluent turbidity vs time for spring runoff water using 6.5 mg/L of Magnifloc 572-C.

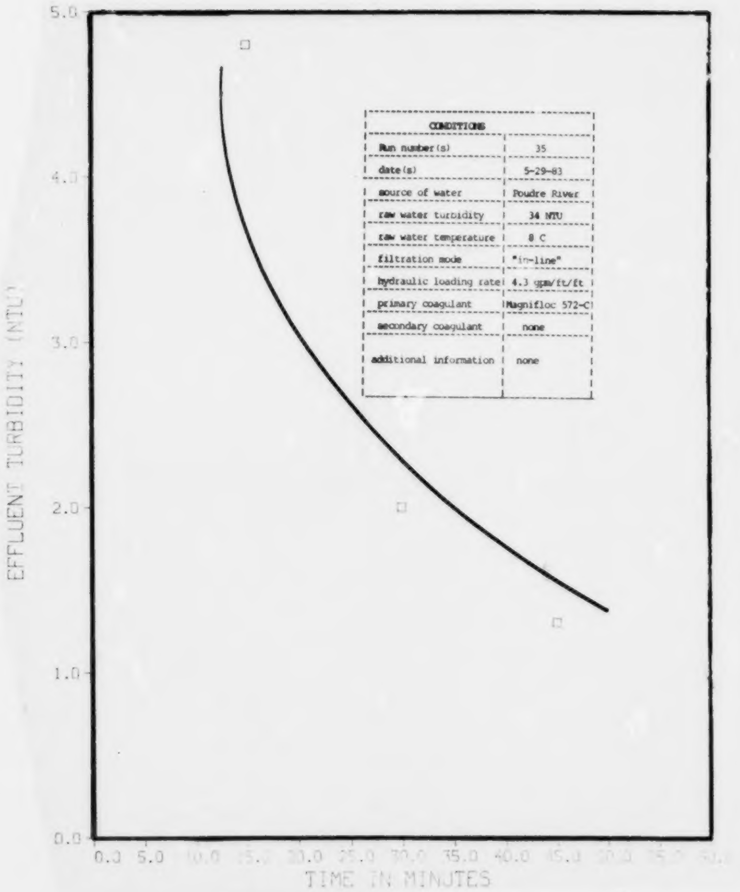


Figure H-24. Effluent turbidity vs time for spring runoff water using 9.0 mg/L of Magnifloc 572-C.

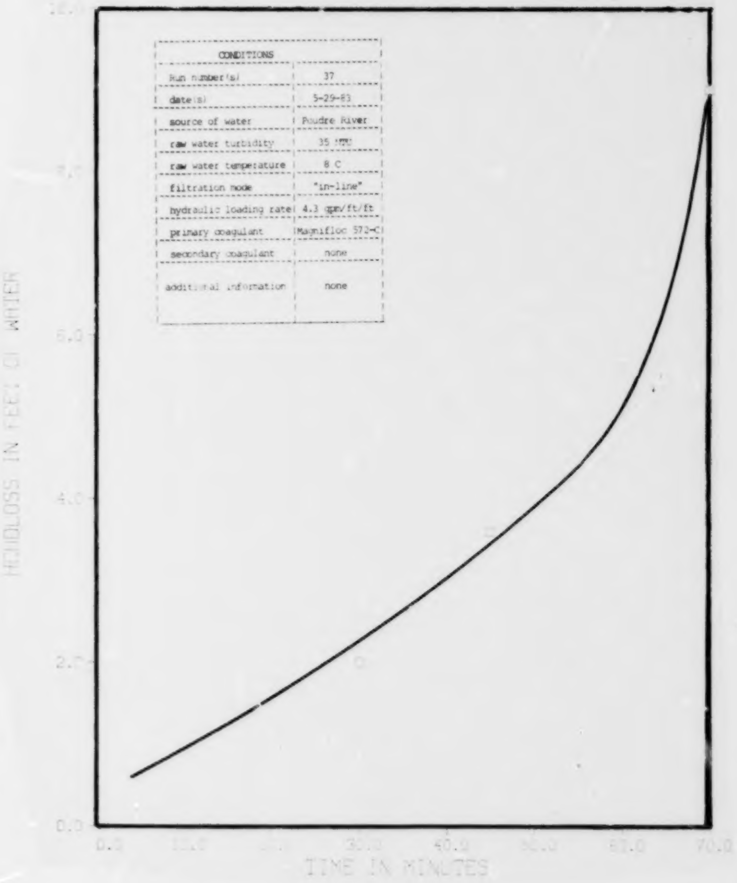


Figure H-25. Headloss vs time without coagulation. Spring runoff water; raw water was 35 NTU.

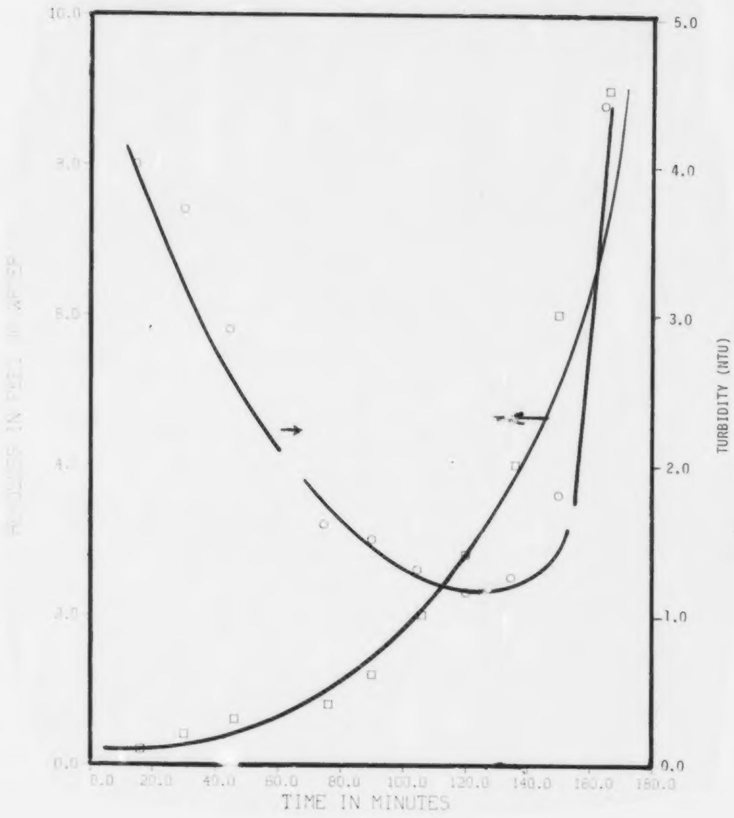


Figure H-26. Headloss and effluent turbidity vs time. Spring runoff water using 7 mg/L of Magnifloc 572-C; raw water was 16 NTU.

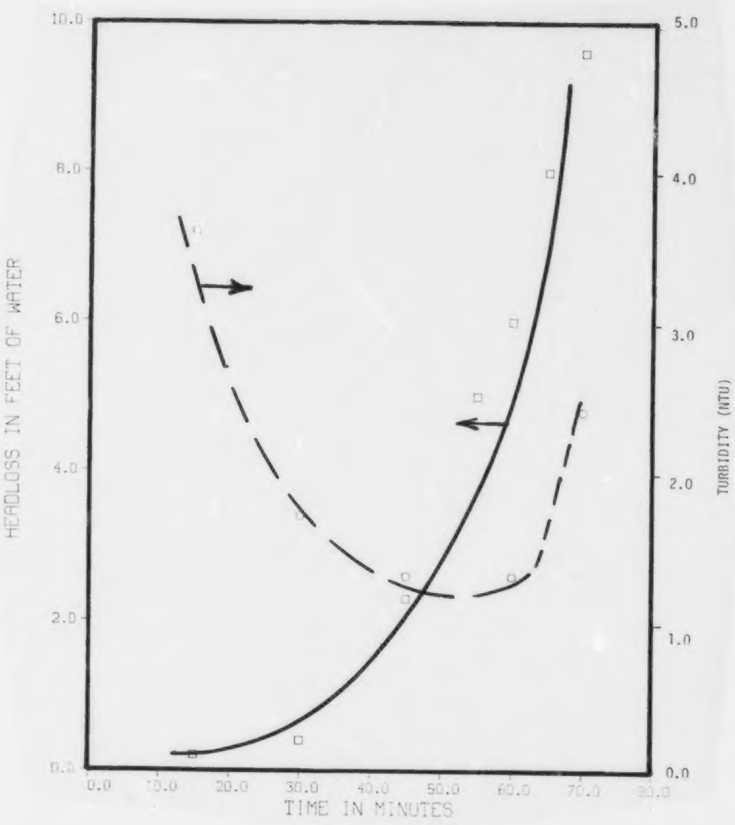


Figure H-27. Headloss and effluent turbidity vs time during spring runoff using 12.5 mg/L of Magnifloc 572-C; raw water was 35 NTU.

development of confidence in the WATER BOY's operation. This confidence was extended to the coliform and Giardia cyst sampling protocols, respectively.

In using Horsetooth Reservoir water the WATER BOY could be setup inside the Engineering Research Center at Colorado State University. This facilitated development of procedures since there was no need to protect against freezing. Also the Engineering Research Center shop and supply room were nearby. For these reasons, Horsetooth water was used to develop the Giardia cyst and coliform bacteria injection and sampling procedures.

HORSETOOTH TESTING

Coagulant Dosage Determination

Four chemical coagulants were used in testing with Horsetooth Reservoir water to obtain curves of effluent turbidity vs dose of coagulant. Table H-1 summarizes the overall results. Figures H-13 to H-16 show the four curves for Magnifloc 573-C, Nalco 8102, Magnifloc 572-C, and alum, respectively. The four curves all have the classical U-shape, permitting determination of "optimum" coagulant dosages. The "optimum" dosages so determined were then used during test runs in which coliform bacteria and Giardia cysts were injected into the influent piping of the WATER BOY. These curves also permitted selection of the "nonoptimum" coagulant dosages, which comprised part of the testing program in which Giardia cyst and coliform bacteria removals were evaluated.

Each of the three polymers used had the capability to reduce turbidity levels from 7.0 NTU, in the raw water, to 0.5 NTU for the product water, after one-hour of operation. After several hours of operation the turbidity levels were reduced to 0.15 NTU. This indicates that the polymers were highly effective in turbidity removal, using raw water from Horsetooth Reservoir. Similar results were obtained in the lab-scale pilot work. Therefore these polymers were expected to be effective in removal of bacteria and Giardia cysts. Alum was tested also, as seen in Figure H-16, producing finished water turbidity of 1.2 NTU, after one hour of operation.

Effect of Coagulant Dose on Filtration

After determination of "optimum" dosages of coagulants, based upon turbidity removal, and after selection of "nonoptimum" dosages to be used in testing, removals of coliform bacteria and Giardia cysts were evaluated using the WATER BOY. This evaluation was performed using coagulant dosages categorized as "none", "optimum", and "nonoptimum". Table H-1 summarizes the turbidity, coliform bacteria, and Giardia cyst removal data from 21 tests classified according to the type of coagulant dosage used.

Zero Coagulant Dose Tests--

The first seven runs of Table H-1, were tests in which "zero" coagulant dose was used, designated as "none". These tests were performed to establish a reference for evaluating Giardia cyst and coliform bacteria removals when coagulants were used.

Results showed that large numbers of cysts passed through the WATER BOY filter when chemicals were not used. Removals of Giardia cysts were less than one percent in three of the seven tests, while two others gave removals of 41 and 84 percent. Results for one of the seven tests showed a removal of >99 percent, which cannot be explained at this time. The results were supported by removals of turbidity and coliform bacteria. Turbidity removals ranged from 3 to 14 percent while coliform bacteria removals were about 30 percent for two tests. Only two coliform removal results are reported in the first seven tests due to difficulties in establishing proper dilutions in the analyses. These results further establish the contention that rapid rate filtration must be preceded by chemical coagulation to ensure effective treatment for production of drinking water.

Optimum Coagulant Dosage Tests--

Ten tests in Table H-1 used "optimum" dosages of coagulant. These ten runs are the second group of tests shown. The first eight tests used only a primary coagulant chemical, and the last two used alum as a primary coagulant and a polymer as a secondary coagulant. The tests using "optimum" coagulant dosages were performed with expectation that high removals of coliform bacteria and Giardia cysts would occur. For these "optimum" dosage tests, Table H-1 shows that removals of turbidity, coliform bacteria, and Giardia cysts all exceeded 90 percent, with only four exceptions, i.e. for turbidity when alum was used either alone or as the primary coagulant.

The data in Table H-1 show that removals of Giardia cysts exceeded 99 percent in five of the eight test runs having Giardia data. Cysts were not detected in the product water in these cases. Removals of less than 99 percent occurred only when alum was used; the reason is not evident. Removals of coliform bacteria exceeded 94 percent in all cases. Turbidity removals exceeded 90 percent with only four exceptions as noted above.

The cyst concentrations it may be noted were 10, 30, 45, 250, 800, 2000, 200, 75 cysts/liter for Runs 49, 52, 58, 90, 92, 98, 105, and 106, respectively. While alum could be less effective than the polymers, the cyst concentrations, which were not controlled easily, partially due to logistic problems, were quite high for the tests with alum. At the same time, however, the turbidity vs alum dose curve, shown in Figure H-16, indicates that alum is less effective as a coagulant than the polymers tested (see Figures H-13, H-14, H-15). These results indicate areas where further research effort is needed; i.e., to both better define the relationships and to explain the behaviors noted.

Nonoptimum Coagulant Dosage Tests--

The "nonoptimum" coagulant dosage tests, which used polymer only, are the last four tests shown in Table H-1. Cysts were not detected in the effluent for any of these "nonoptimum" Giardia test runs, while turbidity removals ranged between 76 and 86 percent, and removals of coliform bacteria ranged from 81 to >99 percent. Runs 51 and 59 used above-optimum dosages of Magnifloc 573-C and Nalco 8102, respectively. Runs 75 and 91 used below-optimum dosages of Magnifloc 572-C and Nalco 8102, respectively. Table H-1 shows the dosages used, which can be related to the turbidity-dose curves in

Figures H-13 to H-16 for the purpose of ascertaining the deviation from optimum. The "nonoptimum" dose tests were run to ascertain the sensitivity of removals of turbidity, bacteria, and Giardia cysts to deviations from optimum coagulant dosages, which could occur in practice. These results indicate that for Horsetooth Reservoir water, removals are not highly sensitive to coagulant dosage, but removals are not as high as when optimum dosages are used.

Associations Between Dependent Variables

Turbidity vs Giardia--

Table H-1 shows results for tests in which Giardia cyst removals were obtained. Figure H-17 shows these data for percent removals of Giardia cysts plotted against percent removal of turbidity. The plot shows that when removal of turbidity is high then removal of Giardia cysts is high also, e.g. exceeding 90 percent. The plot shows also that low removals of Giardia cysts occurred only when removals of turbidity were low also. The curve shown was drawn to indicate an association between the group of plotted points in the upper right portion of the plot and a fewer number of points in the lower left; it has no statistical significance. The curve shown has a rationale, however, based upon the work of Al-Ani and Hendricks (1983), which shows a similar association in a three-dimensional histogram plot. Their work shows that generally when turbidity removal exceeds 80 percent, Giardia cyst removal will exceed 98 percent. This work, at the field scale, supports their findings, except Figure H-17 indicates that Giardia removals exceed 90 percent (not 98 percent) when turbidity removal exceeds 80 percent. This supports generally their contention that turbidity removal can be used as a surrogate for Giardia cyst removal.

Coliform vs Giardia--

Table H-1 shows results for 10 tests in which coliform bacteria removals were obtained along with corresponding removals of Giardia cysts. Figure 3-6 is a plot showing percent removal of Giardia cysts vs percent removal of coliform bacteria. The plot shows that when removals of coliform bacteria are high then removals of Giardia cysts are high also. Only one point was obtained for low removals. The curve shown was drawn to indicate an association between the one point on the left side and the group of points on the right. These results are consistant also with those of the laboratory-scale testing and support the contention that removal of coliform bacteria can serve as an indicator of removal of Giardia cysts. The results indicate that when high removals of turbidity or coliform bacteria occur, then effective filtration is likely.

Turbidity vs Coliforms--

Figure H-19 shows plotted points, also obtained from Table -1, for percent removal of turbidity vs percent removal of coliform bacteria. The association between the two groups of plotted points is similar to the previous two plots, i.e. if 80 percent removal of turbidity occurs then removal of coliform bacteria can be expected to exceed 95 percent.

Coliforms vs Standard Plate Count--

Standard plate count measurements for the influent and effluent streams were made for only two runs, Runs 51 and 52. Removals were 99 percent and 98 percent, respectively with influent concentrations 29,000/mL and 15,000/mL. Removals of coliform bacteria were >99 percent and 95 percent for these two runs. Standard plate counts were not run routinely since coliform bacteria data were used and it was necessary to set priorities in order to control the work load.

Effect of Run Time on Filtration Effectiveness

Coliform bacteria concentrations in the product water were measured at intervals of time in Run 59. This was done during the initial 70 minutes of filter operation after backwash. Figure H-20 is a plot of the data obtained. The coagulant dosage was "nonoptimum", i.e. 11.0 mg/L of Nalco 8102. Figure H-20 shows that coliform counts in the effluent water dropped to 10/100 mL within 20 minutes of operation; this compares with 1200/100 mL in the influent water.

Figure H-21 shows how both headloss and effluent turbidity vary with time during Run 78 using optimum dosage of Nalco 8102 polymer. As shown in Figure H-21, 10-hours were required for the effluent turbidity to reach the lowest value of 0.15 NTU, while a turbidity level of 0.4 NTU was reached at 1-hour after backwashing. Breakthrough occurred about 14-hours after the start of the run, as indicated by the steep slope of the turbidity-time curve. Headloss increased continuously to about eight feet of water, which existed when breakthrough occurred.

After 12-hours of filtering during Run 78 Giardia cysts and coliform bacteria were fed into the system (at this point the run was designated as Run 79). Cysts were not detected in the effluent stream. Coliform counts were 8700/100mL in the influent, and 50/100mL in the effluent, giving >99 percent removal. It was not the purpose to have a prolonged run time, as is desired in practice. The purpose of Run 79 was to test the effectiveness of a "well-seated" filter in removing Giardia cysts and coliform bacteria.

RESULTS FROM SPRING RUNOFF TESTING AND FAMILIARIZATION TESTING - FIELD-SCALE

This appendix material summarizes results obtained in April and May 1983 during spring runoff of the Cache La Poudre River, when turbidity levels ranged from 12 to 44 NTU. The results are contained in this appendix to illustrate the contrast in treating high turbidity water compared with the low turbidity water, the focus of the research. The results indicate that although "in-line" filtration can produce water of 1 NTU, run times were only about two hours. Since run times of only two hours are not economical, the "in-line" mode is not feasible for treating high turbidity waters. The question was explored because of its significance if found feasible for high turbidity waters as well as waters having low turbidity.

SPRING RUNOFF RESULTS

During spring runoff, turbidity levels of the Cache La Poudre River ranged between 12 and 44 NTU, changing as much as 10 NTU in one hour, and water temperatures ranged between 7 and 10°C. Since the WATER BOY was set up on the river when spring runoff began in late April 1983, it was decided to take advantage of these different conditions and conduct turbidity testing. The idea was to ascertain whether the "in-line" mode of filtration was effective for high turbidity waters.

There were 22 effluent turbidity vs chemical dose test runs using Cache La Poudre River water during spring runoff. Table H-2 summarizes the spring runoff results according to coagulant dose category. Testing was not done using Giardia cysts and coliform bacteria because of the limited scope of this phase. Eighteen test runs were conducted using Magnifloc 572-C polymer as sole coagulant, and four tests used alum as the sole coagulant. The alum test runs, Runs 39 to 42, were deemed invalid due to excessive dilution of the alum feed solution. The 18 effluent turbidity vs chemical dose tests, using Magnifloc 572-C as the sole coagulant involved two comparisons between the bench scale, laboratory scale, and field scale pilot plants (reported by McElroy and Hendricks, 1984). Three headloss and effluent turbidity vs time curves were developed.

Effect of Coagulant Dose on Filtration

Figure H-22 shows the effluent turbidity vs chemical dose curve developed using Magnifloc 572-C and water from the Cache La Poudre River during spring runoff. From this curve, the optimum dosage range for Magnifloc 572-C was estimated to be between 6 and 20 mg/L. This optimum dosage range is defined by turbidity removal, as shown in Figure H-22. The curve shown in Figure H-22 is unique for the particular ambient water conditions tested. Results, shown in Table H-2, are summarized in the following sections.

Zero Coagulant Dose Tests--

Runs 34 and 36 had zero coagulant dose. Raw water turbidities were 23 NTU and 35 NTU, respectively. These are the first two runs listed in Table H-2. After one-hour of operation, the effluent turbidity for these no chemical runs were 10 NTU, for Run 34; and 11 NTU for Run 36.

Optimum Coagulant Dose Test--

The optimum dose range was determined to be 6 to 20 mg/L of Magnifloc 572-C for 27 NTU spring runoff water. Runs 25, 27b, 28a, 29, 30, 33, 35, 37, and 38, had coagulation dosages within this 6 to 20 mg/L optimum dose range. Turbidity removals for these nine optimum dose runs ranged between 93 and 97 percent.

Nonoptimum Coagulant Dose Tests--

Runs 23, 24, 26, 27a, 28b, 31, and 32, all had nonoptimum coagulant dosages, as determined with 27 NTU raw water. None of these nonoptimum dose runs had effluent turbidity below 3 NTU. Turbidity removals ranged between 44 and 94 percent.

Effect of Time on Filtration

Five effluent turbidity and headloss vs time runs were conducted using spring runoff water from the Cache La Poudre River. These were Runs 33, 35, 36, 37, and 38.

The results of Run 33 is shown in Figure H-23, which shows how effluent turbidity varies with time immediately following backwashing for raw water having 23 NTU. Effluent turbidity readings declined steadily to 1.4 NTU, 1.2 NTU, and 0.9 NTU, at 10 minutes, 30 minutes, and 60 minutes, respectively. Figure H-24 shows the results of Run 35, which was similar to Run 33, but with 34 NTU water. Both Figures H-23 and H-24 illustrate the need for "filtering to waste". A period of about 30 minutes duration appears adequate based upon the curves shown.

Figure H-25 shows how headloss varies with time without chemicals for the "in-line" mode of filtration, and using raw water having turbidity of 35 NTU. Figure H-26 and H-27 show headloss and effluent turbidity vs time relations using an optimum dose of Magnifloc 572-C, "in-line" filtration, and raw water turbidity of 16 and 35 NTU respectively.

Figures H-25, H-26, and H-27 are the results of Runs 36, 38, and 37, respectively. The length of run for these three runs, before backwashing was required, were approximately 60 min, 160 min, 60 min, respectively. These short runs show that "in-line" filtration is not a suitable treatment mode during spring runoff. Conventional treatment would allow flocculation which would permit sedimentation, thus reducing the turbidity load on the filters.

APPENDIX I

CHEMICALS

Coagulant chemicals are described in this appendix, which includes manufacturer's literature as available. Also, because it is often not clear how alum is expressed, e.g. as mg/L AL^{+++} or mg/L $Al_2(SO_4)_3$, etc., a chart of equivalents is shown.

The alum and the polymers used are indicated below by manufacturer and brand name.

Manufacturer	Brand Name	Literature Included
Allied	Liquid alum	yes
Nalco	650	yes
	8100	no
	8102	yes
	8152	yes
	8170	no
	8181	no
Dow	Separan NP10	yes
American Cynaid	Magnifloc 572C	yes
	Magnifloc 573C	yes

PROPERTIES OF LIQUID ALUM

Allied Chemical

CUSTOMER ENGINEERING
TECHNICAL SERVICE INDUSTRIAL CHEMICALS DIVISION
P.O. BOX 6, SOLVAY, N.Y. 13209

September 1, 1972 SHEET 1 OF 6

DATA SHEET LA-1 - EQUIPMENT AND PIPING FOR LIQUID ALUM AT AMBIENT TEMPERATURES

A. PHYSICAL PROPERTIES

1. Description

Liquid alum, an aqueous solution of aluminum sulfate, $Al_2(SO_4)_3$ plus H_2O, is a very pale green liquid. The commercial strength, 36.5° Baume', has 8.3% available Al_2O_3.

2. Physical Constants

Density (gm/cc) at 60°F	1.34
Density (lb/gal) at 60°F	11.2
Gallons/ton at 60°F	180
Viscosity (cp) at 32°F	52
Viscosity (cp) at 70°F	21
Boiling point (°F)	214
Freezing point (°F)	5

3. Conversion from Dry Alum

There are 5.4 pounds of dry alum (17% Al_2O_3) per gallon of liquid alum. Convert dry alum to liquid alum as follows:

$$\frac{\text{pounds dry basis}}{\text{5.4 pounds per gallon}} = \text{gallons liquid basis}$$

CALCULATIONS SHOWING EQUIVALENT CHEMICAL EXPRESSIONS FOR ALUM CONCENTRATION

According to the Allied Data Sheet I-1, Appendix I, the density of the liquid alum is 1.34 gm/mL at 60°F. The data sheet states that the density of dry alum is 5.4 lb dry alum (17 percent Al_2O_3) per gallon of liquid alum. The converson of these data to concentrations of Al_2SO_4 or Al_2O_3 are not apparent. The conversions are explained as follows:

1. Determine percentage of dry alum in liquid alum solution:

$$\frac{5.4 \text{ lb dry alum}}{\text{gal liquid alum}} \times \frac{\text{gal liquid alum}}{8.34 \text{ lb water} \cdot 1.34 \dfrac{\text{lb liquid alum}}{\text{lb water}}}$$

$$= \frac{4.5 \text{ lb dry alum}}{11.17 \text{ lb liquid alum}} = \frac{0.48 \text{ gm dry alum}}{\text{gm liquid alum}}$$

2. Deduce form of "dry alum"

The MW of $Al_2(SO_4)_3 \cdot 14H_2O$ is 592

The MW of Al_2O_3 is 102

The Al_2O_3 equivalent weight in $Al_2(SO_4)_3 \cdot 14H_2O$ is $= \frac{102}{592}$

$$= 0.172 \frac{\text{gm } Al_2O_3}{\text{gm} Al_2(SO_4)_3 \cdot 14H_2O}$$

This means that the "dry alum" has the form $Al_2(SO_4)_3 \cdot 14H_2O$ per gm liquid alum, or

$$\frac{0.48 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}{\text{gm liquid alum}} \times \frac{1.34 \text{ gm liquid alum}}{\text{mL liquid alum}}$$

$$= \frac{0.643 \text{ gm alum as } Al_2(SO_4)_3 \cdot 14H_2O}{\text{mL liquid alum}}$$

3. Equivalent expressions are:

$$[Al^{+++}] = \frac{0.643 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}{\text{mL liquid alum}} \times \frac{54 \text{ gm } Al^{+++}}{592 \text{ gm} Al_2(SO_4)_3 \cdot 14H_2O}$$

$$= \frac{0.058 \text{ gm } Al^{+++}}{\text{mL liquid alum}} \times \frac{\text{mL liquid alum}}{1.34 \text{ gm liquid alum}}$$

$$Al_2(SO_4)_3 = \frac{0.64 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}{\text{mL liquid alum}} \times \frac{396 \text{ gm } Al_2(SO_4)_3}{592 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}$$

$$= \frac{0.428 \text{ gm } Al_2(SO_4)_3}{\text{mL liquid alum}}$$

$$Al_2O_3 = \frac{0.64 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}{\text{mL liquid alum}} \times \frac{102 \text{ gm } Al_2O_3}{592 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}$$

$$= \frac{0.11 \text{ gm } Al_2O_3}{\text{mL liquid alum}}$$

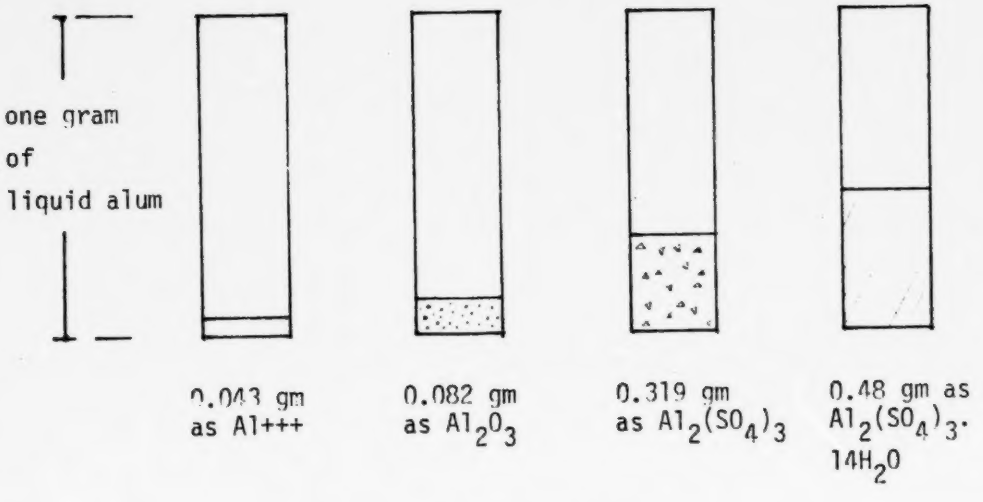
It is possible that operators may express concentrations in terms of mg/L of liquid alum. To do this, the actual weight of liquid alum is used as the basis and is added to water to make one liter of solution. For example, to make 10 mg liquid alum/L solution we find the volume of liquid alum solution that has 10 mg. This is calculated as follows:

$$\frac{X \text{ mL liquid alum}}{10 \text{ mg liquid alum} \times \frac{\text{gm}}{10^3 \text{ mg}}} = \frac{1 \text{ mL liquid alum}}{1.34 \text{ gm liquid alum}}$$

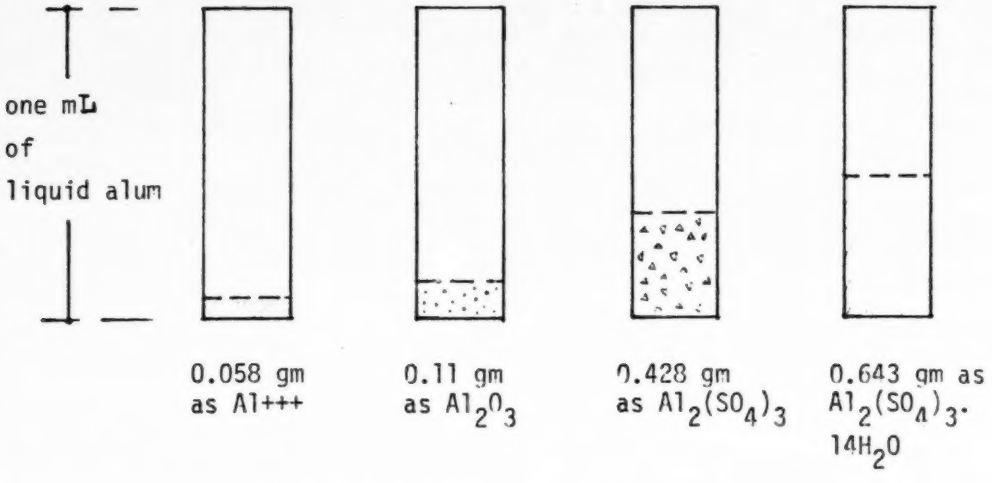
$X = 0.00746$ mL

Of course we can not measure volumes this small so if the liquid alum solution is diluted to say 1.34 gm/1000 mL the volume would be 7.46 mL instead.

The results of all of the above arithmetic are summarized in Figure I-3. Thus, using Figure I-1 (a), it is easy to convert from "grains of liquid alum" to any form of expression desired, e.g., grains as Al^{+++}, $Al_2(SO_4)_3$, etc. For example, if an operator says he uses 10 mg/L of alum, and it is determined that he or she means liquid alum, one merely multiplies this figure by 0.48 to get the dosage in terms of $Al_2(SO_4)_3 \cdot 14H_2O$. Similarly, if we wish to meter alum in terms of say, $Al_2(SO_4)_3 \cdot 14H_2O$, we can consult Figure I-3 (b) and note that each milliliter of liquid alum contain 0.643 gm of $Al_2(SO_4)_3 \cdot 14H_2O$. If the specifications for the liquid alum are different than stated in this Appendix, the above calculations can be used as a model. For example, if the density of liquid alum happens to be say 1.45 (an arbitrarily chosen number) instead of 1.34, all preceding calculations and Figures I-1 (a) and I-1 (b) would be changed accordingly.


one gram
of
liquid alum
0.043 gm as Al+++
0.082 gm as Al_2O_3
0.319 gm as $Al_2(SO_4)_3$
0.48 gm as $Al_2(SO_4)_3 \cdot 14H_2O$

(a) One gram of liquid alum


one mL
of
liquid alum
0.058 gm as Al+++
0.11 gm as Al_2O_3
0.428 gm as $Al_2(SO_4)_3$
0.643 gm as $Al_2(SO_4)_3 \cdot 14H_2O$

(b) One milliliter of liquid alum

Figure I-1. Equivalent expressions of alum in Allied Chemical Commercial liquid alum based upon molecular weight conversions.

MANUFACTURER'S LITERATURE ON POLYMERS USED

(1) Nalco 650 (p. 1 of 1)

NALCO®

650

COAGULANT AID

Product Bulletin A-650

NALCO 650 functions as an effective aid for adsorbing oils, clay, organics (including color) and microorganisms. It is particularly effective when used in combination with cationic polyelectrolyes, such as NALCO® 600, NALCOLYTE® 603, 605, or 607, and with inorganic coagulants, such as sodium aluminate. NALCO 650 rapidly forms a fast-settling floc, and should be considered whenever increased throughput is desired. It neither increases the dissolved solids content nor alters the pH of the water being treated.

PRINCIPAL USES

NALCO 650 is a highly surface-active colloid used principally as a complementary coagulant aid and weighting agent in water clarification and softening. NALCO 650 is used extensively where natural turbidity is insufficient to form heavy, low water content floc. The floc thus formed is more readily dewatered or dried than that formed by metallic salts such as alum or iron salts. As a consequence, a decrease in alum or other salt dosage may result, with a lower resulting cost

GENERAL DESCRIPTION

A processed montmorillonite. Forms a uniform, insoluble suspension when dispersed in water.

Form	Pulverized
Color	Light buff
Odor	None
Density	61 lb/cu ft

DOSAGE

Varies between 5 and 50 ppm, depending upon application.

FEEDING

For batch preparation, make up to a 6% slurry in water, by adding NALCO 650 through a 1" screen. To facilitate wetting, the addition of 0.01 lb of NALCO® 680 sodium aluminate per gallon of water, before addition of NALCO 650, is recommended. Feed into the vortex of a Lightnin' or equal mixer. Mix vigorously, initially, then continue slow mixing to maintain a uniform suspension.

In dry chemical feeders where solids are fed continuously. NALCO 650 flows freely in standard proportioning equipment. For optimum results, introduce NALCO 650 into the slurry vat via a Nalco Type III Coagulant Disperser. Make certain that the disperser effluent stream is fed into the vortex of the Lightnin' mixer in the slurry vat. The Lightnin' mixer should have two standard propellers to insure adequate agitation.

Introduce the NALCO 650 slurry into the rapid agitation section of the clarifier or to the suction side of the raw water supply pumps.

HANDLING AND SHIPPING

No special precautions are required, but avoid prolonged contact. Does not deteriorate with age. Store in a dry place. NALCO 650 is shipped in bulk hopper bottom cars, hopper trucks, or in 50 lb multiwall bags.

NALCO CHEMICAL COMPANY
WATER TREATMENT CHEMICALS
2901 BUTTERFIELD ROAD ◻ OAK BROOK, ILLINOIS 60521

SUBSIDIARIES IN AUSTRIA BRAZIL CHILE COLOMBIA FRANCE HOLLAND ITALY MEXICO PHILIPPINES SAUDI ARABIA SPAIN SWEDEN VENEZUELA AND WEST GERMANY ◻ AFFILIATES IN AUSTRALIA CANADA JAPAN SOUTH AFRICA TAIWAN AND UNITED KINGDOM

Registered Trademarks of Nalco Chemical Company ◻ Printed in U.S.A. 3-79
© 1979 Nalco Chemical Company ◻ All Rights Reserved

NALCO

(2) Nalco 8102 (p. 1 of 2)

NALCOLYTE 8102 is a moderate molecular weight, cationic polyelectrolyte developed for both potable water clarification and waste treatment systems.

NALCOLYTE 8102 aids in:

- *Improving effluent quality*
- *Reducing or eliminating the need for metal salts*
- *Producing a dense, rapid-forming, easily settled floc*
- *Forming a compact, easily dewatered sludge*
- *Producing quality water in prechlorinated systems*
- *Reducing or eliminating the need for pH adjustment*

NALCOLYTE®
8102
POTABLE
WATER
COAGULANT

PRINCIPAL USES

NALCOLYTE 8102 is a moderate molecular weight, polycationic polymer recommended for use as a primary coagulant in raw water clarification and lime softening. NALCOLYTE 8102 is approved by the USEPA for treatment of potable water at an application rate up to 50 ppm.

Application Programs	Use
• Conventional Clarification or Lime Softening	Primary coagulant to partially or completely replace inorganic salts
• Direct Filtration	Primary coagulant for low turbidity and colored water
• Filter Aid	Secondary coagulant to improve filter effluent quality
• Clay/Polymer	Primary coagulant in a total alum or iron replacement

Your local Nalco representative can help determine the best clarification program for your needs.

GENERAL DESCRIPTION

Form	Liquid
Charge in Solution	Cationic
Density (Typical)	9.09 lb/gal
Color	Pale amber
Appearance	Slight haze
Odor	Slight
pH Neat (Typical)	4.5
Viscosity	See Figure 1
Freeze Point (Neat)	14°F
Freeze-Thaw Recovery	Complete

DOSAGE

The specific dosage of NALCOLYTE 8102 will depend on raw water characteristics, the type of application, equipment operation, and the results required. Your Nalco representative will recommend the dosage ranges expected for your system.

FEEDING

Conventional Clarification, Clay/Polymer, Direct Filtration

NALCOLYTE 8102 can be fed neat or as a diluted stock solution. See Figure 2. Use a positive displacement pump, BIF 1711 Series or equivalent, to meter the product or solution into a water line where it can be continuously diluted to 0.5% or less before application. NALCOLYTE 8102 should be applied prior to the rapid mix zone to ensure efficient distribution into the water.

When preparing a stock solution in cold water (less than 60°F) additional mixing may be required. NALCOLYTE 8102 solutions greater than 10% concentrations are stable for one week.

Filter Aid Application

NALCOLYTE 8102 should be fed as a 10–30% solution to the distribution header prior to the filters. In some cases better performance can be obtained by feeding each filter individually at the inlet flume. The feed point should be selected to ensure distribution of the polymer within the water prior to filter contact.

Nalco 8102 (p. 2 of 2)

MATERIALS OF CONSTRUCTION

PVC feed lines should be used when handling concentrated NALCOLYTE 8102. Stainless steel pump heads can be used. Store NALCOLYTE 8102 in fiberglass (DK-411 or equivalent), polyethylene, or rubber-lined tanks. If existing mild steel tanks are used, line with Plasite 4005 or equivalent. Consult your local representative for recommended tank designs.

SHIPPING AND STORAGE

NALCOLYTE 8102 is available in bulk or 55-gallon, nonreturnable lined drums. Drums can be stored for one year in unopened containers. Although freezing is harmless, it should be avoided, since lower temperatures increase product viscosity.

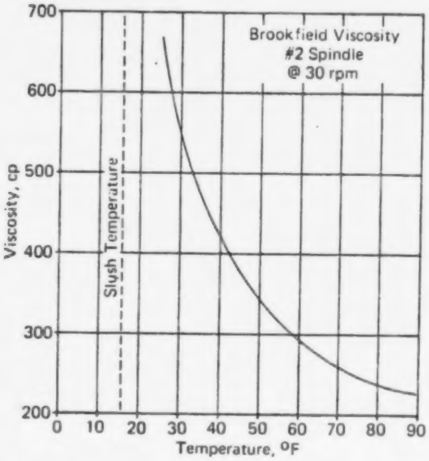
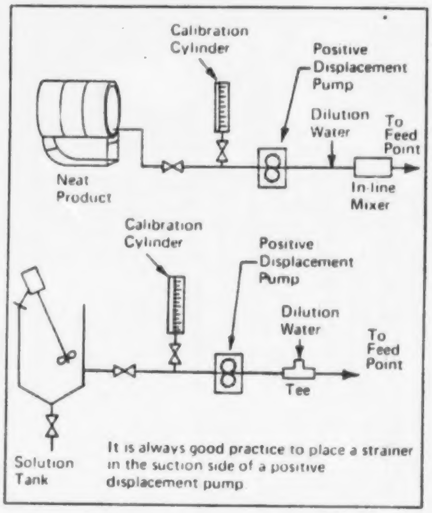


FIGURE 1 – *Typical viscosity as function of temperature NALCOLYTE 8102*

HANDLING

NALCOLYTE 8102 should be handled as a mildly acidic product. Avoid contact with skin, eyes, and clothing. Use in a well ventilated area. Avoid prolonged or repeated breathing of vapors and do not take internally. In case of contact with skin, wash with water. For eyes, wash with water for 15 minutes and call a physician.

NOTE: This bulletin shall not be construed as recommending the infringement of any patent, or extending any license, expressed or implied or assuming any liability under any issued or pending patent.



Calibration Cylinder
Positive Displacement Pump
Dilution Water
To Feed Point
Neat Product
In-line Mixer
Calibration Cylinder
Positive Displacement Pump
Dilution Water
To Feed Point
Tee
Solution Tank

It is always good practice to place a strainer in the suction side of a positive displacement pump.

FIGURE 2 – *Recommended coagulant feed systems*

(3) Nalco 8152 (p. 1 of 1)

NALCO®

8152

COAGULANT AID

Product Bulletin A 8152

NALCO 8152 is a highly active colloid that provides excellent performance in water systems where the floc is not dense enough to settle. NALCO 8152 is recommended in raw water clarification of low turbidity systems or in waste water clarification.

PRINCIPAL USES

NALCO 8152 is recommended as a complementary coagulant aid and weighting agent in water clarification where the natural turbidity is insufficient to form a dense floc. NALCO 8152 is also used in primary and secondary waste clarification. NALCO 8152 is particularly effective when used in combination with Nalco cationic polyelectrolytes.

GENERAL DESCRIPTION

Forms a uniform, insoluble suspension when dispersed in water.

Form	Pulverized
Color	Grayish tan
Odor	None
Bulk Density:	
Loose	27 lb/cu ft
Packed	57 lb/cu ft

DOSAGE

Dosage varies between 2 and 30 ppm depending on application.

FEEDING

For batch preparation, make up a 1–5% slurry in water by the slow addition of NALCO 8152 into the vortex of a high speed mixer. Once the clay is in suspension the agitation can be reduced to maintain uniformity. For continuous feeding, meter the clay into the vortex of a high speed meter (Double prop, 1725 rpm) which thoroughly wets and slurries the clay. The recommended retention time is 40–60 minutes before the slurry is educted or pumped to the application point.

HANDLING AND SHIPPING

Avoid prolonged or repeated breathing of dust. If dusting is a problem, wear an approved dust mask or respirator for protection against pneumoconiosis. NALCO 8152 does not deteriorate with age. Store in a dry place.

NALCO 8152 is shipped in 50 pound multi-wall bags and in bulk.

NALCO CHEMICAL COMPANY
INDUSTRIAL DIVISION :: WATER TREATMENT CHEMICALS
2901 BUTTERFIELD ROAD :: OAK BROOK, ILLINOIS 60521

SUBSIDIARIES IN AUSTRIA, BRAZIL, COLOMBIA, FRANCE, ITALY, MEXICO, PHILIPPINES, SPAIN, SWEDEN, UNITED STATES, VENEZUELA, AND WEST GERMANY. AFFILIATES IN AUSTRALIA, CANADA, HOLLAND, JAPAN, SOUTH AFRICA, TAIWAN, UNITED KINGDOM AND UNITED STATES.

NALCO Registered Trademarks of Nalco Chemical Company Printed in U.S.A. 11 77

NALCO

(4) Magnifloc 572C (p. 1 of 4)

MAGNIFLOC 572C

flocculant

Water
Clarification
Treatment

MAGNIFLOC® 572C flocculant is a low molecular weight liquid cationic flocculant which is effective as a primary coagulant in raw water clarification and is especially effective on low-turbidity/highly colored waters.

Advantages

- Easy to apply, pourable liquid which simplifies dilution, feed and handling operations
- Economical to use — effectiveness at low dosage levels results in reduced handling and storage costs. Added savings can be realized in bulk deliveries
- Works over a wide pH range and eliminates the need for post-treatment pH adjustment.
- Resistant to chlorine
- Eliminates alum or ferric muds when used as a primary coagulant
- Forms a low volume, compact, high-solids sludge which is often biodegradable and burnable
- Less blow-down of sludge is required resulting in more useable water and increased effective throughput

Application

MAGNIFLOC 572C flocculant should be metered to the system by use of a corrosion-resistant, positive displacement pump and diluted 100:1 with clean water prior to being fed to the process stream. Best results are obtained by dispersing feed stream and promoting high turbulence for rapid mixing beyond the addition point.

Principal Uses

MAGNIFLOC 572C flocculant is a highly effective cationic polyelectrolyte which may be used as a primary flocculant or as a coagulant aid in clarifiers and other types of gravity settling operations and in air flotation units.

MAGNIFLOC 572C flocculant is recommended for use in:

- Raw water clarification and especially for low turbidity, highly-colored waters, as a total or partial replacement for inorganic coagulants.
- Treatment of oily waste waters and emulsions as a demulsifier.
- Clarification of latex wastes.

Treatment Level

Raw water clarification	1.0 - 10 ppm
Waste water treatment	1.0 - 20 ppm
Demulsification	10 - 250 ppm

Typical Properties

Appearance	Straw-colored liquid
Specific Gravity (25°C)	1.14 - 1.18
Viscosity (25°C, cps)	100 - 125
pH	5.7
Solubility	Infinite in water
Chemical Reactivity	Non-reactive
Shelf-Life	12-24 months
Freezing Point (°F)	0

Environmental Properties

BOD (mg/L)	100,000
COD (mg/L)	200,000

AMERICAN CYANAMID COMPANY • Water Treating Chemicals • Wayne, N.J. 07470 • (201) 831-1234

Magnifloc 572C (p. 2 of 4)

Handling

Animal tests have shown that MAGNIFLOC 572C flocculant has a low order of toxicity, and is not irritating to skin or eyes. Consequently, no more than ordinary measures of personal hygiene and plant housekeeping are needed in handling this product. Spilled polymer on floors, etc. is very slippery and difficult to "hose down" spills should be scooped and/or wiped up prior to flushing with water. Storage in glass, stainless steel, plastic or epoxy-lined vessels is recommended. Do not use aluminum or iron in feed or storage systems. If MAGNIFLOC 572C flocculant freezes during shipment or storage, it may be thawed and used after agitation to insure homogeniety.

Shipping

MAGNIFLOC 572C flocculant is shipped in 55 gallon non-returnable steel drums, F.O.B. Avondale, La. and Kalamazoo, Mich. For information on bulk delivery, contact your Cyanamid Representative or Sales Office.

Technical Service

Good water management for you and for our environment depends on using the best products and the latest technology in a totally balanced program. At Cyanamid, we offer a full system of water treatment products designed to meet your needs. Your Cyanamid Sales Representative stands ready to offer information and assistance in using this product and helping you achieve our common goal — clean water.

EPA

MAGNIFLOC 572C flocculant is approved by the Environmental Protection Agency for use in the clarification of potable water at dosages of up to 10 ppm.

Important Caution

The information and statements herein are believed to be reliable but are not to be construed as a warranty or representation for which we assume legal responsibility. Users should undertake sufficient verification and testing to determine the suitability for their own particular purpose of any information or products referred to herein. NO WARRANTY OF FITNESS FOR A PARTICULAR PURPOSE IS MADE.

Nothing herein is to be taken as permission, inducement or recommendation to practice any patented invention without a license.

AMERICAN CYANAMID COMPANY • Industrial Chemicals & Plastics Division • Wayne, N.J 07470 • (201) 831-1234

5-1384 7M 10/75

CYANAMID

MSDS NO. 1869-01
CAS NO.
DATE: 08/03/82

MATERIAL SAFETY DATA

PRODUCT IDENTIFICATION	TRADEMARK:	**MAGNIFLOC® 572C Flocculant**
	SYNONYMS:	Polyquaternary amine
	CHEMICAL FAMILY:	Cationic polyamine
	MOLECULAR FORMULA:	Mixture
	MOLECULAR WGT.:	Mixture

WARNING SPILLS OF THIS PRODUCT ARE VERY SLIPPERY

HAZARDOUS INGREDIENTS

COMPONENT	CAS. NO.	%	TWA/CEILING	REFERENCE
No Permissible Exposure Limits (PEL), have been established by OSHA				

NFPA HAZARD RATING Not Established

HEALTH HAZARD INFORMATION	EFFECTS OF OVEREXPOSURE:	Acute oral (rat) and acute dermal (rabbit) LD50 values are 5.36 ml/kg and >16.0 ml/kg, respectively. No eye irritation and no significant skin irritation were produced during primary irritation studies with rabbits.
	FIRST AID:	No specific first aid procedures are necessary for accidental exposure to this product.

EMERGENCY PHONE: 201/835-3100

AMERICAN CYANAMID COMPANY, WAYNE, NEW JERSEY 07470

MSDS NO. 1869-01
MAGNIFLOC® 572C Flocculant

FIRE AND EXPLOSION HAZARD INFORMATION	FLASH POINT: METHOD:	>200 F (>93.3 C) Closed Cup
	FLAMMABLE LIMITS (% BY VOL):	Not Available
	AUTOIGNITION TEMP:	Not Available
	DECOMPOSITION TEMP:	Not Available
	FIRE FIGHTING:	Use water, carbon dioxide or dry chemical to extinguish fires. Wear self-contained, positive pressure breathing apparatus and full firefighting protective clothing.
REACTIVITY DATA	STABILITY: CONDITIONS TO AVOID:	Stable None known
	POLYMERIZATION: CONDITIONS TO AVOID:	Will Not Occur None known
	INCOMPATIBLE MATERIALS:	Strong oxidizing agents. This material reacts slowly with iron, copper and aluminum, resulting in corrosion and product degradation.
	HAZARDOUS DECOMPOSITION PRODUCTS:	Thermal decomposition or combustion may produce carbon monoxide, carbon dioxide, ammonia, oxides of nitrogen and/or hydrogen chloride gas.
PHYSICAL PROPERTIES	APPEARANCE AND ODOR:	Straw colored liquid; slight amine odor
	BOILING POINT:	Not Available
	MELTING POINT:	0 F (−18 C)
	VAPOR PRESSURE:	Not Available
	SPECIFIC GRAVITY:	1.14-1.18
	VAPOR DENSITY:	Not Available
	% VOLATILE (BY VOL):	≈50%
	OCTANOL/H_2O PARTITION COEF.:	Not Available
	pH:	5-7 as is
	SATURATION IN AIR (BY VOL):	Not Available
	EVAPORATION RATE:	Not Available
	SOLUBILITY IN WATER:	Complete
SPILL OR LEAK PROCEDURES	STEPS TO BE TAKEN IN CASE MATERIAL IS RELEASED OR SPILLED:	Spills of this material are very slippery. Cover spills with some inert absorbent material and scoop into a container. Wash area thoroughly with water. Repeat if slipperiness remains.
WASTE DISPOSAL	Disposal must be made in accordance with applicable governmental regulations.	
SPECIAL PRECAUTIONS	HANDLING AND STORAGE/OTHER:	None

Marvin A. Friedman Marvin A. Friedman, Ph.D., Director of Toxicology and Product Safety

This information is given without any warranty or representation. We do not assume any legal responsibility for same, nor do we give permission, inducement, or recommendation to practice any patented invention without a license. It is offered solely for your consideration, investigation and verification. Before using any product read its label.

(5) Magnifloc 573C (p. 1 of 4)

Water Clarification Treatment

MAGNIFLOC®
573-C COAGULANT

POTABLE GRADE

PRODUCT BULLETIN WTC 115

MAGNIFLOC 573-C is a liquid cationic flocculant which works effectively as a primary coagulant in raw water clarification or as a powerful coagulant aid in the clarification of water such as surface waters common to Texas and Louisiana.

ADVANTAGES

- Easy to apply, pourable liquid which simplifies dilution, feed and handling operations.
- Economical to use — effectiveness at low dosage levels results in reduced handling and storage costs. Added savings can be realized in bulk deliveries.
- Works over a wide pH range and eliminates the need for post treatment pH adjustment.
- Resistant to chlorine.
- Eliminates alum or ferric muds when used as a primary coagulant.
- Forms a low volume, compact, high-solids sludge which is both biodegradable and burnable.
- Less blow-down of sludge is required resulting in more useable water and increased effective throughput.

PRINCIPAL USES

MAGNIFLOC 573-C is a highly effective cationic polyelectrolyte which may be used as a primary flocculant or as a coagulant aid.

MAGNIFLOC 573-C is recommended for use in:

- Gravity Settling Operations — improves floc formation yielding larger floc size and faster settling rates.
- Clarifiers of all types.
- Air Flotation — Results in clearer underflows and greater through-put.
- Solids-liquid separation systems containing residual chlorine up to several ppm.
- Settling basins.

APPLICATION

MAGNIFLOC 573-C should be metered to the system by use of a corrosion resistant, positive displacement pump and diluted 100:1 with clean water prior to being fed to the process stream. Best results are obtained by dispersing feed stream and promoting high turbulence for rapid mixing beyond the addition point.

TREATMENT LEVEL

When used as the primary coagulant, treatment ranges from 1.0–10 ppm. Normally, MAGNIFLOC 573-C is more effective if added prior to the lime slurry.

CYANAMID WATER TREATING CHEMICALS, WAYNE, N. J. 07470

Magnifloc 573C (p. 2 of 4)

TYPICAL PROPERTIES

Appearance	Straw, liquid
Specific Gravity (25°C)	1.14 – 1.18
Viscosity (25°C, cps)	200 – 400
pH	6 – 8
Solubility	Water –
Chemical Reactivity	Non-reactive
Shelf Life (50° – 100°F)	6 Months

PRELIMINARY ENVIRONMENTAL PROPERTIES

BOD (mg/L)	100,000
COD (mg/L)	200,000
Odor Threshold No.	115
Taste Threshold No.	8,500

HANDLING

Animal tests have shown that MAGNIFLOC 573-C has a low order of toxicity, and is not irritating to skin or eyes. Consequently, no more than ordinary measures of personal hygiene and plant housekeeping are needed in handling this product. Spilled polymer on floors, etc. is very slippery and difficult to "hose down" – spills should be scooped and/or wiped up prior to flushing with water.

SHIPPING

MAGNIFLOC 573-C coagulant is shipped in 55 gallon non-returnable steel drums. F.O.B. Avondale, La. For information on bulk delivery, contact your Cyanamid Representative or Sales Office.

TECHNICAL SERVICE

Tech[illegible] service and information for making the best use of this product are available through your Cyanamid P[illegible]tative.

SALES OFFICES

P.O. Box 868
Mobile, Ala. 36601
(205) 342-4622

P.O. Box 3381
Portland, Ore. 97208
(503) 228-6231

P.O. Box 31
Linden, N.J. 07037
(201) 486-6000

P.O. Box 8889
Chicago, Ill. 60666
(312) 827-8871

1550 Tennessee Street
San Francisco, Cal. 94107
(415) 826-8150

4337 N. American Street
Philadelphia, Penn. 19140
(215) 455-0700

This information is not to be taken as a warranty or representation for which we assume legal responsibility nor as permission, inducement or recommendation to practice any patented invention without a license. The information is offered solely for your consideration, investigation and verification.

CYANAMID INDUSTRIAL CHEMICALS AND PLASTICS DIVISION
WAYNE, NEW JERSEY 07470

1-1354 3M 5/71

CYANAMID

MSDS NO. 1868-01
CAS NO. -----------
DATE: 10/13/82

MATERIAL SAFETY DATA

PRODUCT IDENTIFICATION		
	TRADEMARK:	**MAGNIFLOC® 573C Flocculant**
	SYNONYMS:	Polyquaternary amine
	CHEMICAL FAMILY:	Cationic polyamine
	MOLECULAR FORMULA:	Mixture
	MOLECULAR WGT.:	Mixture

WARNING SPILLS OF THIS PRODUCT ARE VERY SLIPPERY

HAZARDOUS INGREDIENTS

COMPONENT	CAS. NO.	%	TWA/CEILING	REFERENCE
No Permissible Exposure Limits (PEL), have been established by OSHA				

NFPA HAZARD RATING Not Established

HEALTH HAZARD INFORMATION

EFFECTS OF OVEREXPOSURE:	Acute oral (rat) LD50 value is 4.67 ml/kg. Acute dermal (rabbit) LD50 value for a similar product is > 10.0 ml/kg. No signs of irritation of sensitization were produced by MAGNIFLOC 573C treated paper during a repeat insult patch test in humans. No eye irritation was produced during primary irritation studies with rabbits.
FIRST AID:	No specific first aid procedures are necessary for accidental exposure to this product.

EMERGENCY PHONE: 201/835-3100

AMERICAN CYANAMID COMPANY, WAYNE, NEW JERSEY 07470

FIRE AND EXPLOSION HAZARD INFORMATION	FLASH POINT: METHOD:	>200 F >93.3 C Closed Cup
	FLAMMABLE LIMITS (% BY VOL):	Not Available
	AUTOIGNITION TEMP:	Not Available
	DECOMPOSITION TEMP:	Not Available
	FIRE FIGHTING:	Use carbon dioxide, dry chemical, or water spray to extinguish fires. Wear self-contained, positive pressure breathing apparatus and full firefighting protective clothing.
REACTIVITY DATA	STABILITY: CONDITIONS TO AVOID:	Stable None known
	POLYMERIZATION: CONDITIONS TO AVOID:	Will Not Occur None known
	INCOMPATIBLE MATERIALS:	Strong oxidizing agents. This material reacts slowly with iron, cooper and aluminum, resulting in corrosion and product degradation.
	HAZARDOUS DECOMPOSITION PRODUCTS:	Thermal decomposition or combustion may produce carbon monoxide, carbon dioxide, ammonia, oxides of nitrogen and/or hydrogen chlorde gas.
PHYSICAL PROPERTIES	APPEARANCE AND ODOR:	Amber liquid; slight amine odor
	BOILING POINT:	Similar to water
	MELTING POINT:	0 F (−18 C)
	VAPOR PRESSURE:	Similar to water
	SPECIFIC GRAVITY:	1.08-1.18
	VAPOR DENSITY:	Similar to water
	% VOLATILE (BY VOL):	≈50%
	OCTANOL/H_2O PARTITION COEF.:	Not Available
	pH:	5 - 7
	SATURATION IN AIR (BY VOL):	Not Available
	EVAPORATION RATE:	Similar to water
	SOLUBILITY IN WATER:	Complete
SPILL OR LEAK PROCEDURES	STEPS TO BE TAKEN IN CASE MATERIAL IS RELEASED OR SPILLED:	Wear impervious boots. Spills of this material are very slippery. Spilled material should be absorbed onto an inert material and scooped up. The area should be thoroughly flushed with water and scrubbed to remove residue.
WASTE DISPOSAL	Disposal must be made in accordance with applicable governmental regulations.	
SPECIAL PRECAUTIONS	HANDLING AND STORAGE/OTHER:	None

Marvin A. Friedman   Marvin A. Friedman, Ph.D., Director of Toxicology and Product Safety

This information is given without any warranty or representation. We do not assume any legal responsibility for same, nor do we give permission, inducement, or recommendation to practice any patented invention without a license. It is offered solely for your consideration, investigation and verification. Before using any product read its label.

(6) Separan NP-10 (p. 1 of 3)

MATERIAL SAFETY DATA SHEET

PAGE: 1

DOW CHEMICAL U.S.A. MIDLAND MICHIGAN 48640 EMERGENCY PHONE: 517-636-4400

EFFECTIVE DATE: 09 OCT 79

PRODUCT CODE: 77669

PRODUCT NAME: SEPARAN (R) NP10 SYNTHETIC POLYMER

MSD: 0290

INGREDIENTS (TYPICAL VALUES-NOT SPECIFICATIONS)	%
SLIGHTLY HYDROLYZED POLYACRYLAMIDE	%
SOLIDS	95
MOISTURE	5

SECTION 1 PHYSICAL DATA

BOILING POINT: DECOMPOSES : SOL. IN WATER: VERY SOLUBLE
VAP PRESS: (MMHG & 20C) NEGLIGIBLE: SP. GRAVITY: ----
VAP DENSITY (AIR=1): NOT APPLIC. : % VOLATILE BY VOL: NOT APPLICABLE
APPEARANCE AND ODOR: WHITE, FREE FLOWING AMORPHOUS SOLID, LITTLE ODOR.

SECTION 2 FIRE AND EXPLOSION HAZARD DATA

FLASH POINT: NONE (TESTED TO 400F): FLAMMABLE LIMITS (STP IN AIR)
METHOD USED: CLEVELAND OPEN CUP. : LFL: NONE UFL: NONE
EXTINQUISHING MEDIA: FOAM, CO2, DRY CHEMICAL, WATER FOG.
SPECIAL FIRE FIGHTING EQUIPMENT AND HAZARDS: NONE.

SECTION 3 REACTIVITY DATA

STABILITY: SOLIDS SOFTEN AT 220-2300. DECOMPOSITION EVIDENT AT 270C. PRODUCTS FORMED ON COMPLETE COMBUSTION: CARBON DIOXIDE, WATER, AND NITROGEN DIOXIDE.
INCOMPATIBILITY: OXIDIZING MATERIAL.
HAZARDOUS DECOMPOSITION PRODUCTS: NITROGEN OXIDES.
HAZARDOUS POLYMERIZATION: WILL NOT OCCUR.

SECTION 4 SPILL, LEAK, AND DISPOSAL PROCEDURES

ACTION TO TAKE FOR SPILLS (USE APPROPRIATE SAFETY EQUIPMENT): SWEEP UP AND SALVAGE AS MUCH AS POSSIBLE.
DISPOSAL METHOD: BURN OR BURY IN ACCORDANCE WITH LOCAL, STATE, AND FEDERAL REGULATIONS.

(CONTINUED ON PAGE 2)

(R) INDICATES A TRADEMARK OF THE DOW CHEMICAL COMPANY

Separan NP-10 (p. 2 of 3)

MATERIAL SAFETY DATA SHEET PAGE: 2
DOW CHEMICAL U.S.A. MIDLAND MICHIGAN 48640 EMERGENCY PHONE: 517-636-4400

EFFECTIVE DATE: 09 OCT 79 PRODUCT CODE: 77669

PRODUCT (CONT'D): SEPARAN (R) NP10 SYNTHETIC POLYMER MSD: 0290

SECTION 5 HEALTH HAZARD DATA

INGESTION: LOW ACUTE ORAL TOXICITY; LD50 (RATS) GREATER THAN 2000 MG/KG.
EYE CONTACT: SLIGHT TRANSIENT IRRITATION ONLY.
SKIN CONTACT: ESSENTIALLY NON-IRRITATING.
SKIN ABSORPTION: NOT LIKELY TO BE ABSORBED IN TOXIC AMOUNTS.
INHALATION: DOW GUIDE 10 MG/M3. POSSIBLE NUISANCE DUST.
EFFECTS OF OVEREXPOSURE: POSSIBLE THROAT DRYNESS.

SECTION 6 FIRST AID--NOTE TO PHYSICIAN

FIRST AID PROCEDURES:

EYES: IRRIGATION OF THE EYE IMMEDIATELY WITH WATER FOR FIVE MINUTES IS GOOD SAFETY PRACTICE.
SKIN: WASH OFF IN FLOWING WATER.
INHALATION: REMOVE TO FRESH AIR IF EFFECTS OCCUR. CONSULT MEDICAL PERSONNEL.
INGESTION: LOW IN TOXICITY, INDUCE VOMITING IF LARGE AMOUNTS ARE INGESTED.

NOTE TO PHYSICIAN:
EYES: MAY CAUSE MILD IRRITATION. STAIN FOR EVIDENCE OF CORNEAL INJURY.
SKIN: NO EFFECT EXPECTED.
RESPIRATORY: INJURY IS UNLIKELY.
ORAL: LOW IN TOXICITY.
GENERAL: CONSULT STANDARD LITERATURE. NO SPECIFIC ANTIDOTE. TREATMENT BASED ON THE SOUND JUDGMENT OF THE PHYSICIAN AND THE INDIVIDUAL REACTIONS OF THE PATIENT.

SECTION 7 SPECIAL HANDLING INFORMATION

VENTILATION: RECOMMEND CONTROL OF DUST TO SUGGESTED GUIDE.
RESPIRATORY PROTECTION: IF REQUIRED, USE AN APPROVED DUST RESPIRATOR.
PROTECTIVE CLOTHING: NONE REQUIRED.
EYE PROTECTION: NOT NORMALLY NECESSARY. SAFETY GLASSES WITHOUT SIDE SHIELDS RECOMMENDED.

(CONTINUED ON PAGE 3)

(R) INDICATES A TRADEMARK OF THE DOW CHEMICAL COMPANY

MATERIAL SAFETY DATA SHEET PAGE: 3
DOW CHEMICAL U.S.A. MIDLAND MICHIGAN 48640 EMERGENCY PHONE: 517-636-4400

EFFECTIVE DATE: 09 OCT 79 PRODUCT CODE: 77669

PRODUCT (CONT'D): SEPARAN (R) NP10 SYNTHETIC POLYMER MSD: 0290

SECTION 8 SPECIAL PRECAUTIONS AND ADDITIONAL INFORMATION

PRECAUTIONS TO BE TAKEN IN HANDLING AND STORAGE: PRACTICE REASONABLE CAUTION AND PERSON CLEANLINESS. PRODUCT BECOMES SLIPPERY WHEN WET. PRACTICE GOOD HOUSEKEEPING AT ALL TIMES TO PREVENT SLIPPERY FLOORS.
ADDITIONAL INFORMATION: REVISIONS 10/09/79 --- FLASH POINT, SKIN CONTACT, SKIN ABSORPTION, INHALATION, VENTILATION, PROTECTIVE CLOTHING.

LAST PAGE

(R) INDICATES A TRADEMARK OF THE DOW CHEMICAL COMPANY

CONSULT THE DOW CHEMICAL COMPANY FOR FURTHER INFORMATION.

THE INFORMATION HEREIN IS GIVEN IN GOOD FAITH, BUT NO WARRANTY, EXPRESSED OR IMPLIED, IS MADE.

APPENDIX J

GIARDIA PROCUREMENT, ANALYSIS AND DETECTION LIMITS

J-1 Processing and Counting

J-2 Membrane Recovery and Detection Limits

J-3 *Giardia* Quantification Trials

J-4 Effect of Pumping on Cyst Recovery

APPENDIX J

GIARDIA CYST PROCUREMENT, ANALYSIS AND DETECTION LIMITS

This appendix contains information on procurement of *Giardia* cysts, including processing of the fecal samples obtained, sampling efficiency by membrane filtration, techniques for processing samples washed from membrane filters for microscopic counting, detection limits, and an overall discussion of sample processing and cyst counting. The material was based upon the work of Dr. Charles Hibler and was written mostly by Dr. Hibler, with portions written by Dr. W. D. Bellamy (e.g. the portion on detection limits, with editing by the authors.

PROCUREMENT OF GIARDIA CYSTS

Securing Giardia Cysts

Giardia cysts were obtaned from fecal samples of infected dogs. Positive *Giardia* samples commonly appear as soft to watery stools but normal, firm stools should not be excluded as possibilities. Puppies about six weeks old are the best source but older dogs, bitches, and kennel dogs break frequently.

Fecal samples were collected in baggies and securely closed with twist-tie type closures. Samples were labeled with the pen number, dog number, etc. for future reference and notifying appropriate personnel of the results. The samples were placed in a cooler with ice and transported to the laboratory.

The sources of fecal samples were:

(1) CHRL - Collaborative Radiological Health Laboratory

Foothills Campus - Beagle Colony
Call Esther 491-8522 ext 29 for clothes in women locker
    Jim Winic 49208522 for information on puppy liters
    (age, births, breeding, etc.)

(2) Humane Society for Larimer County

6317 Kyle Ave., Fort Collins 226-3647
Collect at 7:30 am (before cage cleaning)
    1:00 pm (after feeding)
Call before collecting to alert staff

(3) Vet. Teaching Hospital

Parasitology Lab 491-7101 ext 233
Glenda Taton (Parasite Lab Tech) will collect
heavy infected samples

(4) Oncology - Vet. Teaching Hospital

Oncology 491-7101
Call Dee or Sharon or Dr. Gillette
They use beagles from CHRL which break with
Giardia when moved to the Vet. Hospital

Preparing Cysts for Experimentation

In the laboratory, zinc flotations were performed on each fecal sample to check for the presence of *Giardia* cysts. This procedure is described below. If cysts were presented, the sample(s) were weighed and added to an equal amount of cool distilled water. The sample was then mixed thoroughly to break apart any aggregates.

If the sample appears extremely dirty it may be filtered through cheese cloth or gauze or the solution may be mixed thoroughly, quickly allowed to settle, poured into another container and the sediment discarded. Each of these procedures will, however, result in the loss of some cysts. Cyst samples and suspensions were refrigerated at all times.

Cyst Identification--

The zinc flotation procedure was used to ascertain the presence of cysts in fecal samples. The procedure is described following. A fecal sample about the size of a pea is placed in a centrigue tube, 5 to 6 drops of Lugol's Iodine is added to the sample and is mixed well. Fill the tube half way with zinc sulfate solution (spgr 1.18 or 1.20) and mix well. Fill the tube with more solution until the meniscus buldges and affix a coverslip. Place the tube in the centrifuge and tap the coverslip with a pencil end to form a secure bond. *If the coverslip is not firmly in place it will come off during centrifugation and the procedure will have to be repeated. *The coverslip must always be handled by its edge as body oils will prevent attachment of the cysts to its surface. Centrifuge the samples at 1500 rpm for 5 minutes. Remove the coverslip and place on a glass slide. Examine the coverslip for *Giardia* at 100x magnification.

Labelling and Storing Cyst Suspensions

Jars containing suspensions of concentrated cysts were labelled with the date and the number of cysts per mL. The sample should be counted at least every 3rd day and before used in experiments to ensure accurate counts and cyst condition.

Cyst Counting Techniques Obtained from Membrane Filter Sampling

There are two techniques used to process a sample obtained from membrane filtering to concentrate the cysts for counting. These are: 1) Stoll dilution, and 2) micropipette. For a sample with a large number of cysts, i.e. a fecal suspension, the Stoll technique is usually used. For a sample with a low cyst population, the micropipette technique usually is used. The zinc flotation technique was used for the first six slow sand filter test runs (see report by Bellamy, et al., 1984) and for identifying cysts in fecal samples.

Stoll Dilution Technique—

The procedure for the Stoll dilution technique is described as follows. Add 3 mL Lugol's Iodine to a Stoll flask and fill the flask to the 56 mL mark with cool distilled water. Mix the fecal suspension well and remove 4 mL liquid. Add the 4 mL to the flask and shake thoroughly. A 0.075 mL aliquot is removed via micropipette and is placed in a vaseline well. A coverslip is affixed and the number of cysts counted at 400x. The total number seen on one slip is multiplied by 200 to give the total number per mL sample. A minimum of 2 coverslips should be read and averaged.

Micropipette Technique for Samples from Experimentation--

The procedure for the micropipette technique is described as follows. Samples in mason jars under ice will arrive at the laboratory and must sit overnight to allow settling of the cysts and debris. The following day the samples are pipetted down to approximately 200 mL liquid without disturbing the sediment. After the excess water is removed, mix the sample well and pour in a 50 mL conical centrifuge tube. Centrifuge for 5 minutes at 1500 rpm. Pipette off the supernant to about 5 mLs and repeat the procedure until all the sample has been concentrated to 1 mL and the sample jar rinsed well with distilled water. The final volume of the concentrate will depend on the amount of debris present in the sample.

To a 1 mL concentrate add 5 to 6 mLs Lugol's Iodine and to a 5 mL sample add 10 to 15 mls Iodine. Mix the sample thoroughly and remove a 0.050 mL aliquot via micropipette. Place in a vaseline well, affix coverslip, and scan entire slip at 400x. Note the characteristics of the debris present (protozoa, amorphous, fungal bodies, etc.) and count the number of cysts if any. If cysts are seen a minimum of two aliquots are counted and averaged.

To calculate the number of cysts present in the entire sample the number is multiplied by its corresponding dilution factor, i.e.

a 1 mL concentrate is multiplied by 20

a 5 mL concentrate is multiplied by 100

and a 10 mL concentrate is multiplied by 200

All results are recorded and reported on the standard forms, e.g. Figure J-1. Information which must be included is: date, information included on the sample label, initials of the analyst, counts of duplicate sample readings, final cyst number reported and the observations of the debris appearance.

Reagents and Supplies

Lugol Iodine

1000 mL warm distilled water
100 gm Potassium Iodine
50 gm Iodine

Mix till Iodine crystals are in solution. Store in dark bottle - light will deactivate the solution.

$ZnSO_4$ Solution

2-3 gallons distilled water
3 kg or 1-6.6 lb jar of $ZnSO_4$ crystals
Mix till crystals are in solution, place hydrometer into solution to read specific gravity. Keep adding $ZnSO_4$ till a specific gravity of 1.18 or 1.20 is reached. Store in one gallon glass jars.

Coverslips

VWR Micro cover glasses 1 ounce
    Cat No. 48366-227
    22 x 22 mm No. 1 1/2

Slides

Scientific Products Micro Slides
Plain Pre-cleaned
1.2 mm thick Size 3 x 1 inch
Cat No. M6130

Micro-pipette Tips

Micro-selectapette pipette tips
Siliconized - For - micro - pipetting
50-75-100 µL 250 pipettes
Clay Adams Re-order No. 4711
Cat No. 53517-423 VWR

GIARDIA QUANTITATION

Filtration System__________

Run Information (sample label)	Analysis Date	Am't. Conc. in Sample	Analysis by	Counts of Replicates	Cyst # Reported	Observations and Comments

Figure J-1. *Giardia* analysis record form.

MEMBRANE RECOVERY EFFICIENCY

Giardia cysts sampling of filter influent and of filter effluent streams were obtained by the use of 5 micrometer pore size Nucleopore R polycarbonate membrane filters. The filters used with the laboratory-scale pilot plant were 142 mm diameter, while 293 mm diameter filters were used wth the field-scale pilot plant. Questions about the recovery efficiency of this technique was addressed in brief experiments and is described here.

Recovery Efficiency of 5 µm Pore Size, 142 mm Polycarbonate Membrane Filters

Several tests were conducted by Dr. Hibler to determine the Giardia cyst recovery efficiency of the membrane filters. Table J-1 summarizes the test results.

The tests were conducted to determine if there was a difference in recovery resulting from different cyst source or resulting from different sampling techniques. Tests 1 and 2 in Table J-1 compared different cyst sources and Tests 2 and 3 compared differences in sampling techniques, i.e., pumping the sample through the membrane filter or sucking the sample through.

These results demonstrate that the variation in recovery of Giardia cysts is a function of the cysts and not the sampling techniques. Test 1 results range from 36 to 54 percent and average 44 percent. Test 2 results (using a different source of cysts) produced recovery results ranging from 74 to 89 percent and averaged 79 percent. This demonstrated the marked effect the cyst source has on recovery. Comparing Test 2 at 79 percent recovery to Test 3 at 81 percent recovery demonstrates the minor variation caused by different sampling techniques.

Tests which complement these results are those which are performed routinely on the filter feed tank during Giardia cyst test runs. Table J-2 summarizes the recovery information developed during the slow sand filter tests (see Bellamy, et al. 1984). Each of these tests represents a different cyst source. Again large variations in recovery, i.e., 18 to 80 percent result when different cysts sources were tested, thus confirming the dependence of recovery on the "state" of the cyst.

The "state" of the cyst and its resultant behavior during the sampling procedure is probably dependent on a number of factors. But, based on our observations and Dr. Hibler's experience, the two most apparent factors are: 1) the source of the cyst, and 2) the age of the cyst.

Based on these results it became apparent that the membrane recovery factor should be determined for each test run and that an average recovery for all test runs should not be used. When a membrane recovery factor for a particular run cannot be calculated, e.g., no influent sample was taken, an average from similar tests has been used.

Table J-1. Cyst concentration by membrane filter sampling compared cyst concentration in source tank as determined by grab sample. Analysis by micropipette technique for both sampling methods. Tests conducted in laboratory of Dr. Charles Hibler, July 1982.

Test Condition and Technique	Run Number	Cyst Concentration Based Upon Grab Sample of Tank (cysts/liter)	Cyst Concentration Resulting from Given Test Condition in the First Column (cysts/liter)	Recovery (%)
1. Cysts concentrated with a pump and membrane filter (cyst batch 1)	1	3,333	1,200	36
	2	3,333	1,800	54
	3	3,333	1,500	45
	4	3,333	1,300	39
	5	3,333	1,550	46
	Average	3,333	1,470	4
2. Cysts concentrated with a pump and membrane filter (cyst batch 2)	1	35,00	25,000	71
	2	35,000	30,000	86
	3	35,000	27,000	77
	4	35,000	26,000	74
	5	35,000	31,000	89
	Average	35,000	27,800	79
3. Cysts concentrated with a membrane filter and vacuum, i.e., no pump (cyst batch 2)	1	35,000	26,000	74
	2	35,000	31,000	89
	3	35,000	28,000	80
	Average	35,000	28,300	81

Table J-2. Comparison of cyst recovered by sampling milk cooler feed tank water using membrane filters with cyst concentrations in tank as computed after adding cyst concentrate suspension. Analyses performed during slow sand filter experiments.

Slow Sand Filter Run Number	Cyst Concentration[1] in Filter Feed Tank	Cyst Concentration Determined by Subsampling the Filter Feed Tank with a Membrane Filter[2]	Membrane Filter Percent Recovery
48	420	196.8	46.8
60	500	399.3	79.9
66	50	35.8	71.7
69	50	31.3	62.6
75	50	15.9	31.8
81	50	32.2	64.3
87	1,000	183.8	18.4
90	1,000	221.0	22.1

[1] Each of these results are the average of 3 to 6 analyses performed on a cyst concentrate of liquefied dog feces which is added to the filter feed tank on a batch basis. Cyst concentraton equals a number of cysts in concentrate suspension divided by volume of water in tank.

[2] Each of these results are the average of 4 to 11 analyses. The samples are concentrated with a membrane filter.

The mathematical determination of the membrane recovery factor is:

100 x (detected cyst conc.)/(known ("added") cyst conc.)

The known ("added") cyst concentration is determined by analyzing a cyst concentration, i.e., liquified dog feces, numerous times, then adding the concentrate to the batch filter feed tank. The concentration in the tank is then calculated by the appropriate dilution factor. The "detected" cyst concentration is then determined by analyzing a sample from the filter feed tank. This sample is concentrated with a membrane filter thus allowing for the membrane recovery calculation. The membrane filter recovery efficiencies given in Table J-2 were determined this way.

Passage of Cyst Through Membrane Filter

A 5-liter glass container was filled with 4 liters of water. The water was cooled to 5°C and dog feces containing *Giardia* cysts were added to the container. The feces added contained a sufficient number of cysts to bring the cyst concentration up to 2500 c/L. One liter of the mixture was then filtered through a 5 µm pore size polycarbonate membrane filter. The filtrate was collected in two 500 mL flasks.

There were no *Giardia* cysts found in either of the filtrate flasks. The entire sample volume was concentrated and analyzed by zinc flotation.

Retention of Cysts on Surface of Membrane Filter After Washing

A portion of the membrane filter used in the above experiment, approximately the area of one cover slip, was examined microscopically after it had been washed; no cysts were seen on the membrane filter. A similar but more in-depth examination was performed by Luchtel et al. (1980). This analysis also showed that very few cysts were retained by the membrane filter after washing.

DETECTION LIMIT DETERMINATIONS

There are two detection limit calculations used for this experimentation: 1) for each individual micropipette analyses, and 2) for an average detection limit when numerous samples are being considered. Each of these methods are discussed below.

Micropipette Detection Limit

The micropipette method of analysis begins by concentrating a sample to one milliliter. In other words all the cysts present in the sample are concentrated to the 1 mL volume. A 0.05 mL (1/20 mL) aliquot is then taken and microscopically examined. This means that if there is only one cyst present in the 1 mL sample concentrate, there is 1/20 chance that it will be withdrawn in the 0.05 mL aliquot. This accounts for the first detection limit factor of: (20)/(Number of aliquots examined). In other words, 20 cysts must be present in the 1 mL, and uniformly distributed, to be sure that one cyst will be withdrawn by one aliquot. If the sample filtered is 100 liters, the detection limit is 20/100, or 0.20 cysts/liter. The total detection limit for a sample on a per liter basis is then calculated by:

[(20)/Number of aliquots]/[(Fractional membrane filter recovery efficiency) (liters of sample concentrated)]

This equation accounts for the analysis dilution, the membrane filter recovery, and the size of sample. For example:

Sample size = 100 liters
Membrane recovery efficiency = 45%
One aliquot analyzed
Detection limit = [(20/1)]/[(0.45)(100)] = 0.44 cyst/liter

Zinc Sulfate Detection Limit

The zinc float method of analysis is characterized by microscopically examining the entire sample for *Giardia* cysts. There is no dilution factor associated with this analysis technique. It did become apparent when comparing this technique to the micropipette technique that it resulted in cyst counts of approximately 20 percent less than the micropipette method. Consequently, the detection limit for zinc float analyses on a per liter basis is calculated by:

(1)/[(0.80)(Fractional Membrane Recovery) (liters of sample conc.)]

This calculation accounts for the 80 percent recovery by zinc flotation, the membrane filter recovery and the size of sample. For example

Sample size = 50 liters
Membrane recovery = 35%
Detection limit = 1/[(0.80)(0.35)(50)] = 0.07 cysts/liter

Average Detection Limit

The average detection limit is used when more than one analysis has been performed for a test run. Rather than physically combining all of the samples into one container and performing one analysis, each sample was analyzed separately and then the results were mathematically combined. This leads to slightly different results but both results are valid. The mathematical approach requires an averaging of detection limits since individual detection limits are not suitable for multiple analyses of the same source. For example, a single source of water is analyzed 100 times for coliforms and none are found in any of the 100 mL samples. The true test accuracy is not demonstrated by reporting the individual test detection limits, i.e. that the source has less than one coliform per 100 mL, when in fact 10 liters of sample were analyzed and no coliforms were found.

The individual detection limit for Giardia analyses is based on the probability of finding one cyst. This can be understood by envisioning the analysis of a thousand 1 mL samples, each having one cyst in them. If one 0.05 mL aliquot is taken from each sample and examined it will be determined, after completing all of the analyses, that there is a one in twenty chance of finding a cyst. The detection limit for each analyses was 20/1 mL or the inverse of the probability of finding one cyst, i.e. 1/20. This factor of 20 is the multiplication factor already discussed.

Since the detection limits are the inverse of the probabilities of finding a cyst it is then appropriate to apply probability calculations to multiply analyses when determining the combined detection limit. The following calculations describe the analysis:

P = Probability of finding one cyst

N = Number of tests

(1-P) = Probability of not finding a cyst

$(1-P)^N$ = Probability of not finding a cyst in N samples

$1-(1-P)^N$ = Probability of finding a cyst in N samples

$1/[1-(1-P)^N]$ = Detection limit for N tests, i.e. inverse of probability of finding a cyst

For example, assume 5 samples were collected with an average membrane recovery factor of 50 percent and that each sample was concentrated from 10 liters.

Individual detection limits = (20 cysts/1 aliquot)/(0.5, membrane recovery factor) = 40 cysts
(only one aliquot was analyzed)

Individual probability of detecting one cysts = 1/40

Average detection limit for the 5 tests = $1/[1-(1-1/40)^5]$
= 8.41 cysts

Average detection limit per liter = 8.41/10 = 0.841 cysts/liter

As an alternative the 5 samples in the above example could have been physically combined and the detection limit would have been:

Individual detection limit = (20/1)/0.5 = 40 cysts
(only one aliquot was analyzed)

Individual detection limit per liter = 40 cysts/50 liter
= 0.8 cysts/liter

This result, as expected, is somewhat lower than the mathematical combination, but for each technique the detection limit is valid.

Detection limits in this report can be for individual analyses or an average for a test run; each is applied to its specific case. An average detection limit is not applied to an individual analysis.

Conclusions

The counting and sampling experiments conducted in July, August and September of 1982 by Dr. C. Hibler, established that the micropipette technique is the most suitable technique for this work. Different samples from the same suspension, different replicates of the sample, and three persons counting resulted in a maximum difference between any two counts of only about fifteen percent. Although there is no suspension of known cyst concentration to use for a standard, it is believed that the counts by this technique represent the Giardia cyst population in the sample counted.

On sampling efficiency, the use of the 5 µm pore size, 142 mm polycarbonate membrane filter represents the best state-of-the-art on sampling at this time. Sampling efficiency of the pump membrane filter system was determined to be primarily dependent on the source and age of cysts being used for a particular experiment. This discovery resulted in the determination of a cyst recovery factor from the membrane filters on a test run by test basis.

GIARDIA QUANTIFICATION TRIALS

This section describes the preliminary Giardia analytical evaluations performed by Charles P. Hibler, Consetta M. Helmick and Donna G. Howell. The purpose was to develop an accurate and reliable means for quantifying cysts of Giardia.

Introduction

Accurate quantification for eggs, larvae and cysts of parasitic organisms is extremely difficult because parasites do not produce eggs and larvae continuously, nor do the cyst-producing forms of protozoan parasites encyst (or produce cysts, depending on the species) on a continuous basis. For example, examination of numerous dogs clinically infected with giardiasis has revealed that cyst production (cysts in feces) may vary from extremely low numbers in a fecal sample taken in the morning, to extremely high numbers in a sample taken at noon: results are inconsistent and vary from hour to hour and day to day. Diarrhea causes dilution, resulting in inaccuracy by some techniques, and compaction also results in inaccuracy. Moreover, cyst numbers in one portion of the fecal mass often are much higher (or lower) than those in another portion. Thus, unlike bacteria which frequently continue to multiply as they pass the digestive system, and can be cultured to obtain accurate counts, uniform mixing of eggs, larvae or cysts does not occur; nor does multiplication occur in the intestinal contents. Quantification of eggs, larvae and cysts necessitates visualization of the organism. Needless to say, experience is a factor, fatigue is a factor, and technique is a factor. If thorough mixing does not occur, or if sampling techniques are poor, inconsistent, or sloppy, the end result is highly variable data.

Parasitologists use two types of techniques for reporting presence or absence of parasites in blood, urine or stool specimens: (1) qualitative, and (2) quantitative. The reason for both qualitative and quantitative techniques is that the presence of parasites in pets and/or humans indicates treatment is necessary; however, since most domestic ruminants and horses, as well as wild species, harbor a few parasites, economics enter into the decision. Irrespective of the technique used, the factors given in the preceding paragraph must be taken into consideration. Moreover, qualifications and experience of the parasitologist in diagnosing parasitism and recognition of a given technique's limitations are additional factors to be considered. Although the author has had 20 years experience diagnosing all of the known types of parasites of man and animals, I will confine my remarks to techniques employed for Giardia.

Qualitative techniques (hopefully) reveal to the parasitologist the presence or absence of parasitic infection. There are a number of qualitative techniques purported to be effective in diagnosing Giardia; however, the actual number of techniqes suitable for this purpose are limited. The direct smear, the Willis technique (and a myriad of modifications on the market, most of which are made to sell rather than diagnose), the formalin-ether sedimentation technique (formalin-ethyl acetate), and the $ZnSO_4$ centrifugal-flotation techniques are those generally employed.

The direct smear, although with obvious limitations, does have a place and can be effectively used by experienced parasitologists, especially when seeking cysts or trophozoites from clinical cases of parasitism if the sample is extremely fresh. Moreover, since some parasitic organisms do not encyst and are too fragile for any flotation technique, (Trichomonas), it is the only means available. The direct smear should not, when negative, be used as the only diagnostic criterion when seeking cysts, eggs, or larvae.

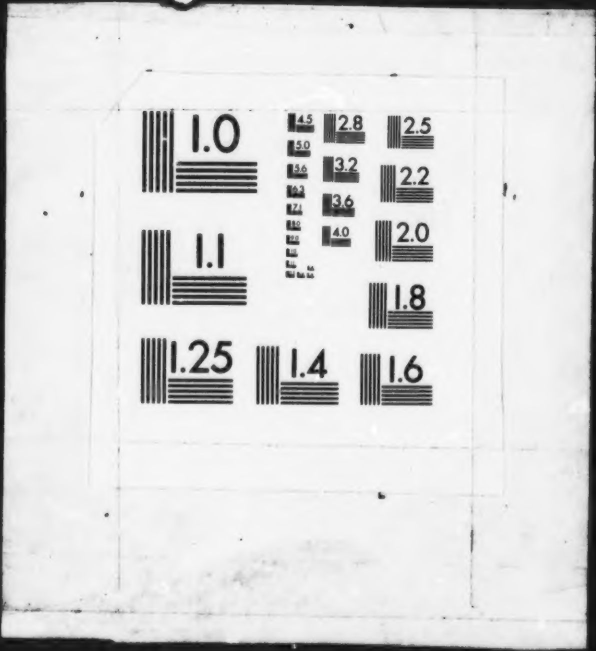
The Willis technique and its many modifications (Fecalyzer, Ovassay, etc.) employ $MgSO_4$, NaCl, $NaNO_3$, or sucrose. These generally are concentrated to a specific gravity of 1.20 to 1.30 (depending upon the chemical) to "float" eggs, larvae and cysts to the surface of a vial, centrifuge tube, etc. They often are allowed to attach to a microscope slide, a coverslip or, alternatively a bacterial loop is used to sample for the presence of organisms in the meniscus. Unfortunately, the chemicals generally used will destroy the fragile cysts of the species of Giardia found in most of the animals of interest (dog, cat, man, beaver, muskrat, etc.). Even if the specific gravity is reduced to 1.17 or 1.18, the great majority of cysts are destroyed. However, if the "overlay" technique is used with sucrose at a specific gravity of 1.13 then cyst destruction in minimal.

The formalin-ethyl acetate sedimentation technique is widely employed by medical technologists, using the excuse that since schistosome eggs are too heavy to float, a sedimentation technique must be employed in the interest of accuracy. The author is not aware of _any_ cases of schistosomiasis occurring among native Americans who have not left the United States; the parasite does not occur in the contiguous 48 states. An advantage of formalin-ethyl acetate is that preservation maintains cysts, eggs, larvae and trophozoites of parasites for extended periods of time, facilitating shipment to a laboratory for diagnosis. Two disadvantages are inherent: (1) The technique does not selectively concentrate _anything_, for 90 percent of the material placed in the centrifuge tube is present in the centrifugate; and (2) Cysts of _Giardia_ will not maintain for more than two weeks in formalin. Thereafter they disappear (cysts probably rupture, although reason says they should not do so in this preservative). Therefore, it must be considered that if only a few cysts are present they would be difficult to find in the centrifugate, due either to the lack of selective concentration or because they possibly will have ruptured before examination was initiated. Nevertheless, in the hands of an experienced parasitologist this is a valuable tool; time consuming, but valuable.

Experienced parasitologists working with _Giardia_ have stated, on numerous occasions and in a considerable number of publications, that the $ZnSO_4$ centrifugal-flotation technique is the only reliable concentration technique available for qualitative examination of stool samples. $ZnSO_4$ is used as a specific gravity of 1.18 when examining fresh (unpreserved) samples and at a specific gravity of 1.20 when examining formalin-fixed specimens. The advantages of $ZnSO_4$ are that you obtain a selective concentration of cysts at the meniscus (or on a coverslip). A disadvantage is that some cysts are trapped in the fecal mass, or do not attach to the coverslip. This is not a severe disadvantage and does not effect reliability of the method. Another disadvantage is that formalin-fixed cysts (if examined before they rupture) are heavier (more dense?) than fresh cysts and do not float as well. Recently, we have discovered a third disadvantage: when cysts are maintained in water for extended periods of time (several weeks) (is this a mature cyst?), while viable and infective, either rupture in $ZnSO_4$, or (as with formalin) become heavier and fail to float well. Possibly the cyst becomes more fragile, even when maintained in water at 5°C, over an extended period of time. However, in the authors (limited) experience, they simply do not float, indicating that density has increased. Mixing _fresh_ stool specimens with water (highly diluted specimen), centrifuging and removing the supernatant, followed by $ZnSO_4$ centrifugal flotation, gives a more accurate estimation of the number of cysts (in this case, per milliliter of suspension) than the examination of the formed stool specimen - _providing_ the specimen is fresh and _providing_ the coverslip is not "greasy." Coverslips marketed by some manufacturers are "greasy" and cysts, eggs, etc., do not attach well. Even though this technique (diluting the specimen with water) approaches quantitative procedures (essentially identical with the modified Stoll technique) it is at best 80 percent accurate in the hands of an experienced parasitologist and much less accurate when done by inexperienced parasitologists who are not aware of the limitations of the technique.

4 OF 4

PB 85 194645


1.0
4.5
5.0
5.6
6.3
7.1
8.0
9.0
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

The $ZnSO_4$ centrifugal-flotation technique, although admittedly qualitative, and not accurate, *provides the only means of selective separation of cysts* from the dirt, debris, plant material, algae, diatoms, pollen, nematode eggs and larvae, crustaceans and their eggs, arthropod parts, and the myriads of protozoa, etc., found in surface waters that are sources of domestic supply. Currently this is the only means to determine if *Giardia* cysts are present, and in what relative numbers, in raw water or finished water. When the concentration of cysts is very low (often 1-5 cysts/gallon) any other analytical system currently available would be like looking for the proverbial needle in a haystack! Indeed, in the examination of raw or finished water obtained during epidemics of giardiasis, any procedure other than the selective concentration technique would be an exercise in futility because when you have 8, 16, or 32 water filters to be examined and the Department of Health begging for results, there are not enough experienced people in the United States to provide the answer. Therefore, the state-of-the-art in the real world is that in surface water there are myriads of organisms, together with *Giardia* and selective concentration is the only reliable means of separation of the cysts from other organisms. In fact, this investigator could care less whether *Giardia* is or is not present: if organisms the size of (or larger than) *Giardia* are present in the raw water, and these same organisms (in about the same quantity) are present in the finished water, then the system is at risk. The $ZnSO_4$ centrifugal-flotation technique is an ideal and very quick method to tell the Department of Health and/or water treatment operator that their filtration and/or treatment system is not removing particulate matter the size of or larger than *Giardia*. Therefore, the system is at risk if *Giardia* is introduced into the water supply.

Parasitologists have used, from time to time, a number of quantitative techniques: (1) McMaster Counting Chamber; (2) Whitlock Paracytometer; (3) Stoll Dilution Technique; and (4) Modified Stoll Dilution Technique for the recovery of eggs, larvae, and cysts. Recently investigators working with *Giardia* have initiated the use of the hemacytometer as well as the direct counting procedure (use of a calibrated micropipette). All of these procedures are simply modifications of similar techniques. All have advantages (depending on the parasite and the host) and all have disadvantages: inaccurate mixing, inaccurate sampling, inexperienced parasitologists, and *inexperience with the parasite the individual is counting* can result in highly variable data. An excellent example is *Giardia*. In any given sample some of the cysts are fresh and "plump," the morphology is excellent; some of the cysts are not fresh, and are not "plump," rather they are distorted (dying or dead). Over time (a short period of time!) a dead or dying cyst may not be recognized by the parasitologist. When using a quantitative (dilution) technique, irrespective of what has been diluted (erythrocytes, leukocytes, or *Giardia* cysts), missing a few can result in highly variable data. Moreover, since *Giardia* cysts are not readily visualized without some form of stain (e.g., Lugol's Iodine), then overstaining, understaining, or the *lack of experience* necessary to realize that live, dying, and dead cysts *all stain differently* will result in variable data.

The technique developed by Stoll requires the use of a special (Erlenmeyer) flask marked at 56 milliliters and at 60 milliliters. Fluid (generally water) is added to the 56 milliliter mark and sufficient fecal matter added (determined by Stoll to be 2 grams) to bring the material to the 60 milliliter mark. This is thoroughly shaken and a 0.075 or a 0.10 milliliter sample removed, the eggs, larvae or cysts counted and multiplied by 200 or 100, respectively, to obtain organisms/gram. Since the Stoll technique is essentially a 1:15 dilution, addition of 4 milliliters of suspenson provides the parasitologist with the number of organisms/milliliter. A modification of this technique is to mix the sample in the flask with a solution of high specific gravity ($MgSO_4$, NaCl, etc.), mix, remove a specific amount, add to a centrifuge tube, affix a coverslip and centrifuge. The coverslip is removed and the organisms counted. The problems inherent in the modification of the Stoll technique are the same as the $ZnSO_4$ centrigual flotation technique.

The McMaster Counting Chamber, and the Whitlock Paracytometer are specially manufactured slides containing coverslips (calibrated) permanently affixed. The Chamber (or well) for these techniques (similar to the hemocytometer) are constructed to hold a specific volume of fluid (such as the chemicals of high specific gravity previously mentioned). The specimen is mixed with the fluid, pipetted into the Chamber, and the organisms allowed to float. The disadvantages are that they might not float or, as is the case with *Giardia*, flotation occurs very slowly. Those that float immediately (being closer to the surface) distort and become unrecognizable, only to sink before the remainder have floated. Therefore, the disadvantages of these two techniques make them essentially of no value for counting *Giardia* and will not be considered further.

While the hemacytometer appears to be a likely candidate for counting *Giardia* cysts, and will be evaluated, there are several inherent disadvantages that perhaps bear discussion at this point. The hemacytometer was designed for counting blood cells; consequently, the volume of liquid held in the chamber is extremely small. If the number of cysts in the sample are not in *sufficient concentration* (such as might be anticipated with erythrocytes and/or leukocytes) to provide accurate results, the end result is highly variable data. Moreover, in the authors experience, most parasitologists do not realize that the cysts of *Giardia* are quite *heavy*. The simple act of mixing a diluted sample, pipetting this sample, and then transferring a small portion to the hemacytometer chamber generally results in inordinately high counts because the cysts settle just enough to affect the results. Moreover, considering once again the volume of the chamber, extremely low cyst numbers result in inordinately low counts.

Since quantitative procedures have not been developed or evaluated for *Giardia*, and because evaluation of experimental filtration and/or treatment systems for removal of *Giardia* necessitate reliable and accurate counting procedures, the purpose of this experiment is to develop accurate procedures and evaluate their reliability when performed by experienced parasitologists. Since all quantitative procedures offering any hope of accuracy and reliability are dilution procedures, the techniques to be evaluated are: (1) Stoll Technique; (2) Micropipette Technique; and (3) Hemacytometer Technique.

Materials and Methods

Source of Giardia--

A large amount of feces was collected from four dogs, each with clinical giardiasis, and the fecal matter mixed with distilled water. The water level was adjusted to 2 liters of suspension. This was then refrigerated at 5°C.

Holding Vat--

A 40 liter tank was filled to the 38 liter level with tap water, the chlorine allowed to evaporate for 1 day, and the vat then refrigerated until the water temperature became 5°C.

Techniques--

As indicated in the introductory remarks, all of the techniques to be evaluated are essentially dilution techniques, irrespective of their name. Since Giardia cysts must be stained to facilitate visualization, Lugol's Iodine was used for this purpose. Needless to say, this necessitated a considerable amount of emperical experimentation to determine the best procedure for staining cysts without interfering with accuracy, reliability, or causing undue distortion, overstaining, or understaining that would likewise affect accuracy and reliablity. Ultimately it was determined that a concentrated solution of Lugol's Iodine (parasitologists use many different modifications of this stain) must be added prior to any attempt at counting.

For any given suspension of material another factor needed to be considered: the amount of organic material present which could interfer with accuracy. If too much organic debris is present, and too many cysts per field, microscope fatigue quickly intervenes resulting in inaccuracies affecting the reliability.

Micropipette--

A calibrated micropipette manufactured by Clay Adams, with calibrations of 0.05, 0.075 ad 0.10 milliliters (Silicone coated glass pipettes #4711) here used throughout for both micropipette (MP) and Stoll dilution technique (SD).

With the MP technique, one milliliter samples were obtained after very thorough mixing, concentrated iodine added, and a 0.05 mL sample withdrawn. This sample was introduced into a vaseline well, a coverslip affixed, and the counts performed. The number of cysts counted, for the 1 mL sample, was multiplied by 20 to obtain cysts/mL.

If the amount of organic debris, and the number of cysts, was too concentrated for accuracy, an additional 4 mL of water was added, making a 1:5 dilution. A 0.05 mL sample removed (as before) and the number of cyst multiplied by 100 to obtain cysts/mL. If the material was still too dense, the sample was diluted to 1:10, a 0.05 mL sample removed and the number of cysts multiplied by 200 to obtain cysts/mL. If further dilution was necessary, either the SD technique (see below) was employed or the original suspension was diluted.

Stoll Dilution Technique--

Iodine was added to a Stoll flask (in about the same proportion as with the MP technique) and the flask filled to the 56 mL mark with distilled water. To this was added enough suspension (4 mL) to bring the volume to 60 mL. This was thoroughly shaken, and a 0.075 mL sample removed, introduced into a vaseline well, a coverslip affixed and the number of cysts counted multiplied by 200 to obtain cysts/mL.

Initial Counting--

The 2 liter suspension of fecal material was counted by the MP and SD techniques before addition to the 38 liters of water. The results were (expressed is cysts/mL):

	MP (1:10 dilution)	SD (1:15 dilution)
	24,600	24,400
	25,000	25,200
	25,400	25,400
Average	25,000	25,000

The 2 liters of suspension, when added to the 38 liters of water (1:20 dilution) should provide 50,000,000 cysts in 40,000 mL of water or 1,250 cysts/mL. After addition of the 2 liters of suspension, the vat was maintained at 5^{o}C. Before removing samples for analysis the vat was thoroughly stirred with a large, flat paddle (12 inches wide) for 1.5-2.0 minutes. A 1 mL sample was obtained for use with the MP technique, and a 4 mL sample for the SD technique. Counting of cysts were performed at 450x for evaluation.

Results

Micropipette--

Counting by the MP technique was performed at 1:1 and 1:5. All counting was performed at 450x. Two (replicates) readings were performed on each sample. The results with 1:1 dilution are tabulated.

Comments--

Direct MP counting at 1:1 is an extremely effective, but very time consuming procedure, primarily because of the amount of organic material present. With some water, which contains a considerable amount of algae, diatoms, pollen, protozoa, etc., it is even more time consuming and requires about 1 hour to do a thorough count. An individual can count about 3 samples before the fatigue factor causes data to become variable.

Table J-3. *Giardia* cysts counted by three individuals using the micropipette technique at 1:1 dilution.

	Individual #1	Individual #2	Individual #3
Sample 1	1180	1140	640
Rep	1180	1160	1680
Sample 2	1240	1120	1100
Rep	1240	1160	1080
Sample 3	1300	1160	1000
Rep	1160	1100	940
Sample 4	1340	1160	1000
Rep	1160	1120	1140
Sample 5	1320	Average 1140	Average 1073
Rep	1180		
Average	1230		

Table J-4. *Giardia* cysts counted by three individuals using the micropipette technique at 1:5 dilution.

	Individual #1	Individual #2	Individual #3
Sample #1			
Replicate	1300	1000	1100
Replicate	1100	1200	900
Replicate	1200	1400	1100
Replicate	1400	1100	1000
Average	1250	1175	1025
Sample #2			
Replicate	1200	1000	1400
Replicate	1400	1100	1200
Replicate	1100	1200	1200
Replicate	1100	1400	1300
Average	1200	1200	1250
Sample #3			
Replicate	1500	1200	1400
Replicate	1100	1100	1100
Replicate	1100	1300	1400
Replicate	1200	1400	1400
Average	1225	1250	1325
Sample #4			
Replicate	1200	1200	
Replicate	1200	1100	
Replicate	1400	1300	
Replicate	1100	1100	
Average	1225	1175	

Dilution of the sample to 1:5 resulted in less debris, required less time and the fatigue factor was lower.

Individuals #1 and #2 are more experienced than individuals #3; moreover, #3 had another assignment and often several days would pass between the examination of samples. She commented that becoming accustomed to looking for cysts after a 2-3 days break from the routine was difficult.

The results, with 1:1 or 1:5, are extremely consistent. As might be expected, there appears to be as much variation between individuals as within individuals.

When very little organic debris was present, counting at 100x was possible, however, the individuals discovered that cysts were often missed causing the data to be variable. A recount at 450x in variable resuled in more accuracy.

Stoll Dilution--

This is essentially the same techniques as the MP, but the dilution factor is 1:15, a rather dilute solution of material.

Comments--

Counting cysts by the SD technique is not as fatiguing, nor is it as time consuming as the MP technique, primarily because of the dilution factor of 1:15; however, accuracy was dependent upon a sufficient number of replicates to obtain a good average. As to be expected, considerable variation occurred within and between individuals. Subsequent trials by the author, reducing the number of cysts (further dilution of the vat sample to an estimated 625 cysts/mL) resulted in even more variation; however, concentration of the vat sample to 2500 cysts/mL indicated that variation in counts was reduced. Tests (replicates) similar to those above were not performed, but it stands to reason that increasing the number of cysts (up to a point!) would increase sampling accuracy, while further dilution would decrease the accuracy.

Considerable time (2 weeks) had elapsed before individual #3 completed her sample #3.

Table J-5. Giardia cysts counted by three individuals using the Stoll technique.

Individual #1	Individual #2	Individual #3	
Sample #1			
Replicate	1200	1400	1800
Replicate		1800	1200
Replicate	800	1400	1600
Replicate	2200	1800	
Replicate	1000	1400	1600
Average	1300	1560	1550
Sample #2			
Replicate	1000	1400	1800
Replicate	1600	1200	1200
Replicate	1400	1400	1200
Replicate	1400	1400	1200
Replicate	0800	1400	1000
Average	1240	1360	1280
Sample #3			
Replicate	1400	1600	1000
Replicate	2200	1800	1000
Replicate	800	1400	1000
Replicate	1000	1200	1000
Replicate	1000	1200	1200
Average	1280	1440	1040

*Cysts were old and had begun to rupture or die.

Hemacytometer—

Initially a 1:5 dilution of the vat sample (250 cysts/ml) was examined with the hemacytometer; however, after repeated samples, no cysts were obtained; therefore, a direct examination of the vat sample (1250 cysts/ml) was attemped, using both stained and unstained cysts. The results were: 0, 0, 0, 0, 1 cysts, 0, 0, 2 cysts, 0, 1 cyst, 0, 0, 0, 0, 1 cysts, 0.

Comments—

The hemacytometer holds a very small volume of liquid. Dilution of a sample to 1000-2000 cysts/ml is far too dilute for any semblance of accuracy. However, if the sample is more concentrated (to what extent I do not know but I suspect in the neighborhood of 10,000-20,000 cysts/ml) no doubt accuracy will increase. Nevertheless, I question the accuracy of the hemacytometer under any circumstances unless the investigator is using extremely clean and/or highly concentrated numbers of cysts. Moreover, it was observed that if cysts were withdrawn from the source, and not pipetted onto the chamber very quickly, the cysts tended to settle to the tip of the pipette. When the small volume is considered, together with the high multiplication factor, this would result in inordinately high numbers of cysts/ml.

Quantification After Passing the Push-Pull Pump and the Nucleopore Membrane--

Evaluation of data on filtration runs indicates a 60 percent loss of cysts, either in the counting accuracy, the vat, the pump, the membrane filter, or during the processing. Therefore, a vat, containing approximately 38 liters of water was placed into a refrigerator at 5°C. A sufficient quantity of cysts were added to obtain approximately 2 cysts/ml. Results (see below) indicated 2.0 cysts/ml in the vat. A series of pump-filter examinations were made on this material. A total of 2 liters of material was pumped through the filters, the pads washed, and then examined at a 1:5 dilution by the MP technique.

The procedure, during trial runs, is to pump the material through the filter pad then aspirate (with vacuum) the liquid remaining in the filter canister on through the pad. Therefore, to determine where losses were occurring, some runs were aspirated, some were not. For one run, material was not pumped through the filter, but directly into a flask.

Number of cysts/ml in the Vat--

To determine the number of cysts/ml in the vat 20 ml samples (1 percent of the proposed filtration samples-2 liters) were examined. The 20 ml samples were concentrated to 1 ml and examined by the MP technique.

The results are given below:

	Total Cysts Recovered	
	Sample #1	Sample #2
Replicate	3	3
Replicate	3	0
Replicate	2	1
Replicate	200	200
Average	2.5	1.5

For a 1:1 MP the correction factor is X20; therefore in Sample #1, the average is 50 cysts in 20 ml or 2.5 cysts/ml and in Sample #2 is 30 cysts in 20 ml or 1.5 cysts/ml. This indicates an average of 2.0 cysts/ml. However, the individual reading sample #2 (CPH) had many interruptions and he (CPH) questions the accuracy of his results. The results indicate 4000-5000 cysts should be present in 2 liters. Two to 2.5 cysts/ml, with 20 ml subsamples, is far too dilute to obtain greater accuracy.

Results Through the Pump and Filter--

A total of 2 liters was passed through the pump at each run. After each filter run, a 20 ml subsample was taken for examination. All counting for the filter-pump trials was done at 1:5 dilution by the MP technique; all counting for the 20 ml subsamples was done at 1:1 by the MP technique. The results are expressed as total cysts present in the sample. The average and percent recovery is also given. Percent recovery was determined, at the time of sampling, by the subsample count using the micropipette technique (Table J-6).

Table J-6. *Giardia* cysts recovered after passage through the push-pull pump and the filter.

Run #	Procedure	2 liter sample				20 ml subsample			
		#1 Replicate	#2 Replicate	Average	(%)	#1 Replicate	#2 Replicate	#3 Replicate	Ave
1	Aspirated	1200	1200	1200	36%	4000	4000	2000	3333
2	Aspirated	1800	1800	1800	54%	2000	4000	4000	3333
3	Not Aspirated	1600	1400	1500	45%	4000	2000	4000	3333
4	Not Aspirated	1200	1400	1300	39%	0	000	6000	3333
5	Aspirated	1700	1400	1550	46%	2000	4000	4000	3333
6	Not Filtered	1700	1500	1600	48%	0	6000	4000	3333

Comments--

These results indicate that 3,333 cysts should have been recovered from the 2 liter filter samples. Recovery percentages ranged from 36-54 percent (Ave: 45 percent). Losses no doubt occur in all steps of the operation as a result of the pump, filter and the subsequent centrifugation procedures to concentrate the filter washings.

A series of 50 ml subsamples were obtained subsequent to the filter runs and concentrated to 1:1 and read by the MP technique. The results were:

Sample Size	#1	#2	#3	#4	#5	Ave
50 ml	100	80	60	80	60	76

An average of 76 cysts in 50 ml = 152 cysts/100 ml or 1.52 cysts/ml, which extrapolates to 3040 cysts in 2 liters. The original subsamples, taken 2 days earlier, indicated there should be 3,333 cysts in 2 liters.

The cysts, when introduced into the vat had been maintained 5 weeks and were excellent, morphologically. However, the results from this sample of cysts indicated that losses due to death and dissolution of cysts was occurring very rapidly. For example, counts on the day the vat was charged indicated 2-2.5 cysts/ml. The next day results were 1.67 cysts/ml. Two days later the results indicated 1.52 cysts/ml. Microscopic examination indicated they were dying and/or dead: no doubt many ruptured before processing was initiated and, as might be anticipated, processing through the pump and filter, followed by centrifugation, destroyed many more. It is reasonable to assume that dying/dead cysts are more fragile than fresh cysts. Yet there is little way to predict when cysts are going to die, for this seems to vary between individual samples. We have observed (over the past 12 years) that some *Giardia* samples will keep for weeks and be in excellent shape; others are gone and/or unrecognizable in less than a week. Maintenance in water increases their life span: some cysts will look excellent (morphologically) for 2 months a 5°C while others are beginning to deteriorate at 2-3 weeks. Some cysts in all samples are no doubt more fragile than others and processing will result in a certain amount of dissolution.

EFFECT OF PUMPING ON CYST RECOVERY

Objective

To determine if a loss and/or destruction of *Giardia* cysts occurs in the process of pumping cysts through the push-pull pump or the nucleopore filter, or if the loss occurs as a result of counting error.

Procedure

As in the preceding trial, a 10-gallon tank was filled with tap water, the chlorine allowed to evaporate and the water refrigerated to 5°C. The tank was then charged with 30 ml of dog feces containing 31,000 *Giardia* cysts/ml or 930,000 cysts (estimated).

The trials were initiated on 9/16/82. A total of five runs were made with the push-pull pump and the nucleopore filter, and one run with the push-pull pump, but no nucleopore filter. Three runs were made with the vacuum pump connected to the nucleopore filter and one run with the vacuum pump, but no nucleopore filter. As in the preceding trial, the number of Giardia cysts/ml was determined prior to the trial, and subsamples from the vat were taken during each trial run.

Results

The results are presented in tabular form. Table G-7 lists the cysts/ml determined prior to the runs, Table G-8 lists the results of the push-pull pump through the nucleopore filter, and Table G-9 lists the results using the vacuum pump to pull material through the nucleopore filter. At the end of all runs, a 2 liter grab sample was counted. The 2 liter sample was counted by the direct micropipette technique, 1:15 dilution. A total of 78,200 cysts were calculated to be present in 2 liters or 39 cysts/ml.

Table J-7. Giardia cysts/ml determined to be present in the tank prior to trial. Direct micropipette counts, 1:1 dilution of 1 cc samples.

	Total (cysts/ml)	Average (cysts/ml)
Sample 1	40	
Replicate	40	40
Sample 2	40	
Replicate	20	30
Sample 3	40	
Replicate	20	30
Sample 4	20	
Replicate	60	40
	Average: 35 cysts/ml	

Discussion

The results of this trial indicate that when fresh Giardia cysts are used together with the push-pull pump or the vacuum pump through the nucleopore filter, there is very little cyst loss and/or destruction if the personnel are conscientious in preparation, washing of the filter disc, and performing sufficient replicate counts. A comparison of the push-pull pump with the 50 ml grab samples indicates that results are consistent: an average of the six samples revealed 26.2 cysts/ml by the push-pull pump and 26.5 cysts/ml by the grab sample. Although some problems developed with the vacuum pump, an average of four samples revealed 23.5 cysts/ml by vacuum pump and 22.7 cysts/ml grab sample.

Unfortunately, examination of the material on this tank trial took an inordinate amount of time to complete, possibly resulting in a loss of cysts. It took approximately 2 to 2.5 hours to read each sample (22 samples) because of the large number of cysts, debris, and microscope fatigue. From the time the trial was initiated, samples taken, and samples analyzed, there was a 1

Table J-8. *Giardia* cysts/mL obtained following the push-pull pump and filtering through the nucleopore filter. All counts performed by direct micropipette, 1:5 dilution.

Run #	H_2O Passed	Pressure	Counts	Cysts/mL	50mL Grab Sample	
					Counts	Cysts/mL
1	2000 mL	10 lbs	50,700	25	1600	32
Rep.			49,800	25	1640	33
Rep.			49,500	25	1680	34
Rep.			50,300	25		
Avg.			50,050	25	1640	33
2	1500 mL	15 lbs	45,400	30	1100	22
Rep.			44,700	30	1200	24
Rep.			43,600	29	1120	22
Rep.			43,700	29		
Avg.			44,350	30	1140	23
3	1500 mL	15 lbs	40,200	27	1220	24
Rep.			39,500	26	1100	22
Rep.			39,800	27	1200	24
Rep.			40,500	27		
Avg.			40,000	27	1173	24
4	1500 mL	15 lbs	39,200	26	1400	28
Rep.			39,800	27	1560	31
Rep.			40,300	27	1500	30
Rep.			39,600	26		
Avg.			39,725	26	1486	30
5	1500 mL	20 lbs	45,700	30	1240	25
Rep.			45,500	30	1160	23
Rep.			45,700	30	1300	26
Rep.			46,000	31		
Avg.			45,725	31	1233	25
6*	2000 mL	0 lbs	35,800	18	1140	23
Rep.			40,200	20	1180	24
Rep.			28,200	14	1200	24
Rep.			37,200	19		
Avg.			35,350	18	1173	24

*Used push-pull pump but not the nucleopore filter

Table J-9. *Giardia* cysts/mL obtained using the vacuum pump to pull sample through the nucleopore filter. All counts performed by direct micropipette, 1:5 dilution.

Run #	H_2O Passed	Counts	Cysts/mL	50 mL Grab Sample	
				Counts	Cysts/mL
1	1200 mL	30,300	25	1040	
Rep.		33,400	28	1020	20
Rep.		30,400	25	1100	22
Rep.		31,600	26		
Averages		31,425	26	1053	21
2	1500 ml	31,100	21	1100	22
Rep.		30,400	25	1180	24
Rep.		30,800	21	1120	22
Rep.		31,500	21		
Averages		31,200	21	1133	23
3	1300 mL	26,500	20	1180	24
Rep.		29,000	22	1200	24
Rep.		27,800	21	1140	23
Rep.		29,500	23		
Averages		28,200	22	1173	24
4*	2000 mL	48,800	24	1100	22
Rep.		52,600	26	1160	23
Rep.		46,200	23	1120	22
Rep.		49,600	25		
Averages		49,300	25	1126	23

Note: Only 4 runs were made because of pump problems.
*No nucleopore filter, only the vacuum pump.

week to 10-day span which could account for cyst loss via death of cysts. Also centrifugation of samples could apply enough pressure to fragile cysts to cause rupturing and cyst loss. The entire trial took 80 working hours to accomplish, from start to finish. The pretrial count indicated 30-40 (Average 35) cysts/ml, and the 2 liter grab sample, analyzed shortly after the trial, indicated 39 cysts/ml; yet all counts after a 2-day lag were within the 23-33 cyst/ml range. This indicated that, over time, cyst loss was occurring. Possibly, this was due to increased fragility because of age of cysts or that a certain percentage of cysts are fragile initially. Nevertheless, cyst loss was consistent irrespective of the procedure.